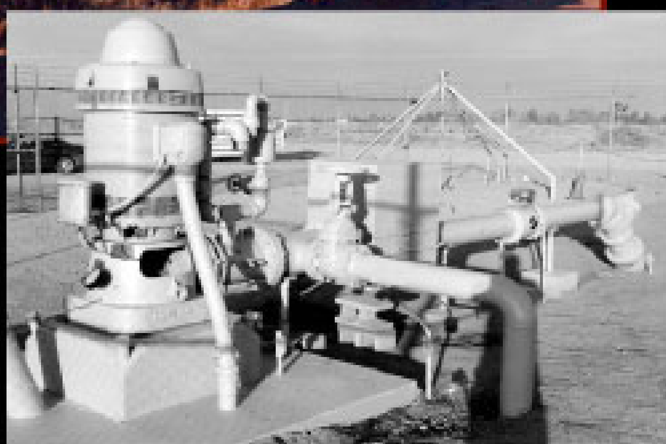
Water-Quality Monitoring and Studies of the Formation and Fate of Trihalomethanes during the Third Injection, Storage, and Recovery Test at Lancaster, Antelope Valley, California, March 1998 through April 1999



U.S. Geological Survey

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Prepared in cooperation with the **Los Angeles County Department of Public Works** and the **Antelope Valley-East Kern Water Agency**

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By Miranda S. Fram[1], Joshua K. Berghouse[1], Brian A. Bergamaschi[1], Roger Fujii[1], Kelly D. Goodwin[2] *and* Jordan F. Clark[3]

U.S. GEOLOGICAL SURVEY

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ANTELOPE VALLEY–EAST KERN WATER AGENCY

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Sacramento, California
2002

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CONVERSION FACTORS, ACRONYMS, ABBREVIATIONS, WATER-QUALITY INFORMATION, AND WELL-NUMBERING SYSTEM

CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

ACRONYMS

AODC, acridine orange direct count

AVEK, Antelope Valley–East Kern Water Agency

DOC, dissolved organic carbon

EPA, U.S. Environmental Protection Agency

LACDPW, Los Angeles County Department of Public Works

MCL, maximum contaminant level

RSD, percent relative standard deviation

$\overline{\text{RSD}}$, mean percent relative standard deviation

STHMFP, specific trihalomethane formation potential

$SUVA_{254}$, specific ultraviolet absorbance at 254 nanometers

SWP, State Water Project

THM, trihalomethane

THMFP, trihalomethane formation potential

USGS, U.S. Geological Survey

UV, ultraviolet

UVA, ultraviolet absorbance

UVA_{254}, ultraviolet absorbance at 254 nanometers

ABBREVIATIONS

$CHBr_3$, bromoform

$CHCl_2Br$, bromodichloromethane

$CHCl_3$, chloroform

$CHClBr_2$, dibromochloromethane

Cl_2, chlorine

CO_2, carbon dioxide

KH_2PO_4, potassium dihydrogen phosphate

N, nitrogen

NH_4Cl, ammonium chloride

SF_6, sulfur hexafluoride

Water-Quality Information

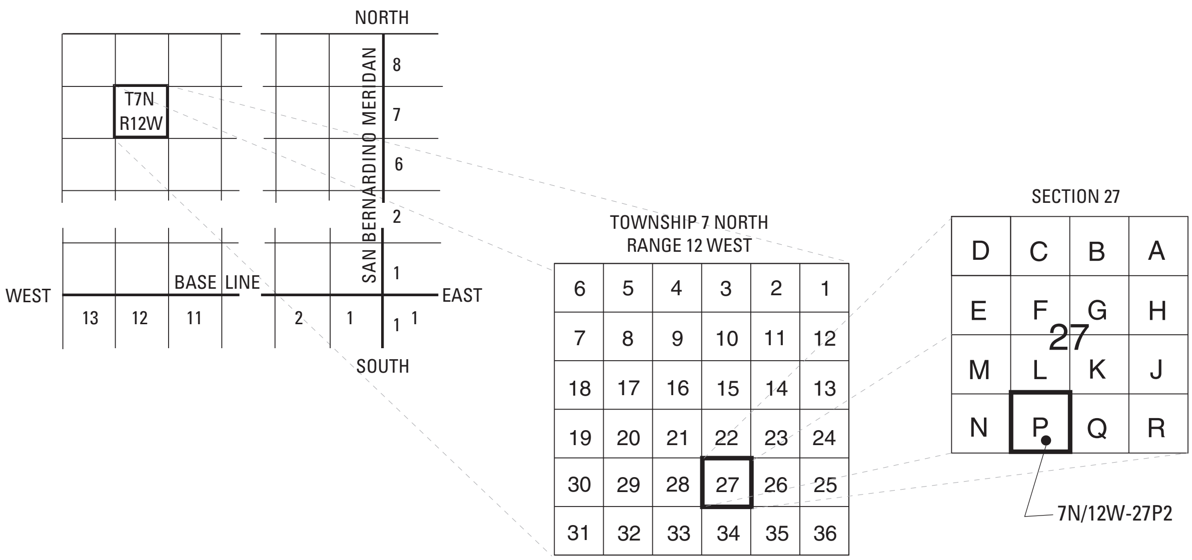
Chemical concentration is given in milligrams per liter (mg/L), micrograms per liter (μg/L), or picomoles per liter (pmol/L). Milligrams per liter is a unit expressing the mass of a solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter, and 1,000 milligrams per liter is equivalent to 1 gram per liter. The numerical value in milligrams per liter is about the same as for concentrations in parts per million, and the numerical value in micrograms per liter is about the same as for concentrations in parts per billion. Micromoles per liter is a unit expressing the number of moles of a solute per unit volume (liter) of water. One million picomoles per liter is equivalent to 1 micromole per liter, and one million micromoles per liter is equivalent to 1 mole per liter.

Ultraviolet light absorbance is given in per centimeter (/cm). Wavelength of light is given in nanometers (nm). Specific ultraviolet absorbance is given in liters per milligram per meter [(L/mg)/m] and is equal to the ultraviolet light absorbance in per centimeter multiplied by 100 and divided by the dissolved organic carbon concentration in milligrams per liter. Specific trihalomethane formation potential is given in millimoles per mole (mmol/mol) and is equal to the trihalomethane concentration in micromoles per liter divided by the dissolved organic carbon concentration in millimoles per liter. Bacterial cell density is given in cells per milliliter (cells/mL).

Specific conductance is given in microsiemen per centimeter at 25°C (μS/cm). Microsiemen per centimeter is numerically equivalent to micromhos per centimeter. Turbidity is given in nephelometric turbidity units (NTU). Gas flow rate is given in milliliters per minute (mL/min). Volume is given in milliliters (mL) or microliters (μL). One thousand microliters is equivalent to 1 milliliter, and 1,000 milliliters is equivalent to 1 liter. Length is given in meters (m) and micrometers (μm). One thousand micrometers is equivalent to 1 millimeter, and 1,000 millimeters is equivalent to 1 meter. Mass is given in micrograms (μg), and one million micrograms is equivalent to 1 gram. Magnetic field strength is given in millitesla (mT).

Well-Numbering System

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with “A” in the northeast corner of the section and progressing in a sinusoidal manner to “R” in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humboldt (H), Mount Diablo (M), and San Bernardino (S). All wells in the study area are referenced to the San Bernardino base line and meridian (M). Well numbers consist of 15 characters and follow the format 007N012W27P002S. In this report, well numbers are abbreviated and written 7N/12W-27P2. Wells in the same township and range are referred to only by their section designation, 27P2. The following diagram shows how the number for well 7N/12W-27P2 is derived.



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Abstract

The U.S. Geological Survey, in cooperation with the Los Angeles County Department of Public Works and the Antelope Valley–East Kern Water Agency, conducted three cycles of injection, storage, and recovery tests to evaluate the feasibility of artificially recharging ground water in the Lancaster area of Antelope Valley, California. During the third cycle (March 1998 through April 1999), the tests included investigations of the formation and fate of trihalomethanes in the aquifer. Trihalomethanes are disinfection by-products formed by reaction between natural dissolved organic carbon that is present in water and chlorine that is added during the drinking-water-treatment process. This report includes a discussion of the design of the investigation; descriptions of the sampling, analytical, and experimental methods used in the investigation; and a presentation of the data collected.

During the third cycle, 60 million gallons of chlorinated water was injected into the aquifer through well 7N/12W-27P2 in the Los Angeles County Department of Public Works well field in Lancaster between April 15 and June 16, 1998. One hundred fifty million gallons of water was extracted from the same well between June 30, 1998, and April 29, 1999. Water-quality samples were collected during the entire cycle from the well and from a nearby set of nested piezometers, and were analyzed for residual chlorine, dissolved organic carbon, trihalomethane, major anion, and dissolved solid concentrations; ultraviolet absorbance spectra; and a number of field water-quality parameters. A statistical analysis was done to evaluate the analytical precision of the residual chlorine, dissolved organic carbon, trihalomethane, and ultraviolet absorbance measurements on these samples. The formation of trihalomethanes in the injection water was examined in laboratory experiments: Trihalomethane concentrations in samples of injection water were monitored during a storage period, and trihalomethane formation potential in the presence of excess chlorine was measured. The role of mixing between injection water and ground water and the conservative or non-conservative behavior of trihalomethanes was studied by adding a conservative tracer, sulfur hexafluoride, to the injection water and monitoring its concentration in the extraction water. The potential for biodegradation of trihalomethanes by aquifer bacteria was assessed in laboratory experiments: Microcosms containing ground water or extraction water and sediment or concentrated bacteria were spiked with trihalomethanes, and the amount of trihalomethanes was monitored during an incubation period. The potential for sorption of trihalomethanes to aquifer sediments was assessed in laboratory experiments: Mixtures of sediment and water were spiked with trihalomethanes, and then the trihalomethane concentrations were measured after an equilibration period.

INTRODUCTION

Ground water is an important source of water supply in Antelope Valley. Since the late 1940s, ground-water pumpage has exceeded natural recharge, resulting in hundreds of feet of water-level declines and more than 6 ft (feet) of land subsidence in some areas (Ikehara and Phillips, 1994). The Antelope Valley augments its over-pumped ground-water supplies with imported water from the California State Water Project (SWP). The SWP is a series of storage reservoirs and aqueducts that transports water from northern to southern California (fig. 1). Facing rapid population growth and increasing demand for the region's water supply, water managers in Antelope Valley are seeking ways to maximize the use of available water supplies. Injecting treated SWP water into the aquifer system during periods of greater surface-water availability to be used later during periods of surface-water deficit is a potential water-supply method for meeting increasing water demands. Using this water-supply method would permit storage of additional imported water during the wet season when surface water is more available. The U.S. Geological Survey (USGS), in cooperation with the Los Angeles County Department of Public Works (LACDPW) and the Antelope Valley–East Kern Water Agency (AVEK), did research and monitoring experiments during three cycles of injection, storage, and recovery in Lancaster, Antelope Valley, California, from September 1995 through April 1999 to assess the feasibility of using this water-supply method in the Antelope Valley (Steven Phillips, U.S. Geological Survey, written commun., 2001; Metzger and others, 2002).

The demonstration tests were designed to investigate how injection, storage, and recovery cycles affect water levels, land subsidence, land-surface deformation, and regional ground-water flow patterns. A cycle consists of three periods: an injection period during which water is injected into the aquifer through a well, a storage period during which the well is idle, and a recovery period during which water is extracted from the aquifer by pumping from the same well. Water-quality monitoring during the first two cycles showed high levels of trihalomethanes in the extracted water during the initial stage of pumping (Los Angeles County Department of Public Works, 2000). Trihalomethanes (THM) are disinfection by-products formed by reaction between natural dissolved organic carbon (DOC) that is present in the water and chlorine that is added during the drinking-water-treatment process. The U.S. Environmental Protection Agency (EPA) regulates the concentrations of THMs and other disinfection by-products in finished drinking water. THM concentrations in the extracted water exceeded the EPA maximum contaminant level (MCL) of 80 μg/L (micrograms per liter) (U.S. Environmental Protection Agency, 1998). LACDPW blended the extracted water with water from other sources to lower THM levels in the water delivered to the consumers to a level below the MCL. The more serious problem, however, was that the extraction water still contained measurable levels of THMs long after continuous pumping had presumably retrieved all the injected water (Los Angeles County Department of Public Works, 2000). This observation raised concerns about the long-term deleterious effect of injection, storage, and recovery on aquifer water quality and thus poses a potential problem for the feasibility of using this water-supply method in the Antelope Valley.

Research and monitoring experiments during the third cycle (March 1998 through April 1999) were expanded to include investigation of the formation and fate of THMs during the cycle. The experiments were designed to address three questions:

(1) What controls the continued formation of THMs in the aquifer after injection?

(2) What causes the continued presence of low levels of THMs in the extracted water after all the injection water has presumably has been retrieved?

(3) Are there natural attenuation mechanisms that can decrease the THM concentrations in the aquifer?

Purpose and Scope

The roles of the USGS in the injection, storage, and recovery tests were to collect and analyze hydraulic and aquifer-system deformation data, to develop a simulation/optimization model to design and manage a larger-scale injection program, and to determine the factors controlling the formation and fate of THMs in the aquifer system. This report presents a description of the project as it pertains to the investigation of the formation and fate of THMs during the third cycle of injection, storage, and recovery. The report describes the analytical methods used and presents all of the data collected for the investigation of the formation and fate of THMs. A series of companion reports will present the other portions of the project. Methods for collection and a compilation of the hydraulic data and the land-surface and the aquifer deformation data are reported by Metzger and others, 2002. Forthcoming reports will present the simulation/optimization model and interpretations of the hydraulic and the deformation data (Steven Phillips, U.S. Geological Survey, written commun., 2001), a description of the use of microgravity surveys to determine water-level changes

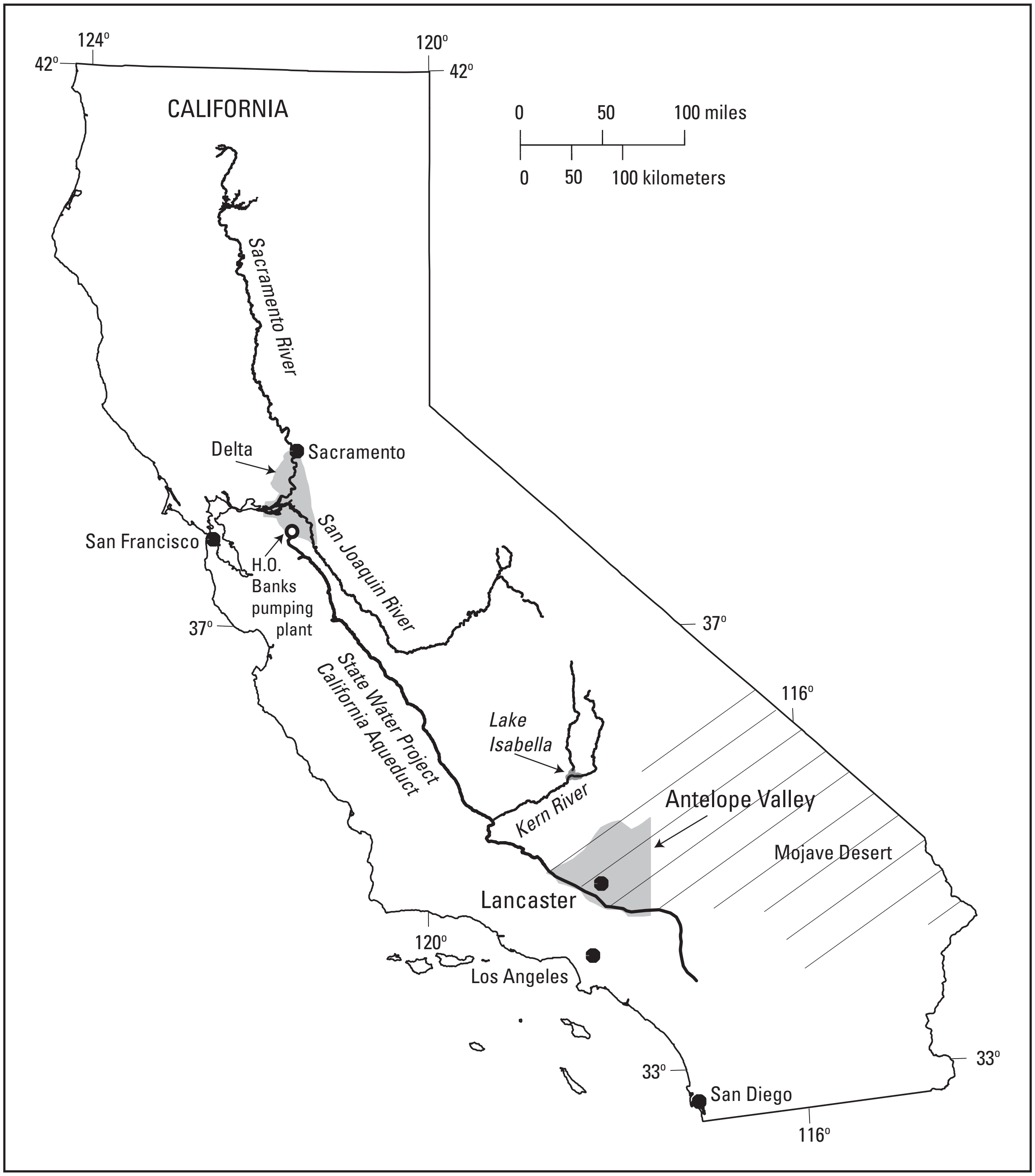

Figure 1. Locations of sites and geographic features relevant to the third injection, storage, and recovery test (March 1998 through April 1999) at Lancaster, Antelope Valley, California.

(James Howle, U.S. Geological Survey, written commun., 2001), and a discussion of the factors controlling the formation and fate of THMs (Roger Fujii, U.S. Geological Survey, written commun., 2001).

Project Design

The investigation consisted of five components, which together addressed the three aforementioned questions concerning the formation and fate of THMs during the third injection, storage, and recovery cycle.

(1) Water-quality monitoring at wells: Water-quality samples were collected periodically from the well used for both injection and extraction to determine the composition of the injection water and, later, the extraction water. Water-quality samples also were collected from a nearby set of four nested piezometers. These samples provided a time series of water-quality data used to delineate the behavior of THMs and other chemical analytes during the cycle.

(2) Formation of THMs from injection water: The potential for continued formation of THMs in the aquifer after injection was investigated by storing injection water for 1–16 weeks under controlled conditions in the laboratory. THM formation potential (THMFP) experiments were done to assess the compositional nature of the THM-forming DOC in the injection water.

(3) Addition of sulfur hexafluoride tracer to injection water: A conservative tracer, sulfur hexafluoride (SF_6), was added to the injection water, and concentrations in the extraction water were monitored. The tracer study was used to evaluate the amount of mixing between the injected water and ground water.

(4) Biodegradation of THMs by aquifer bacteria: The potential for biodegradation of THMs in the aquifer was investigated in laboratory microcosms created using sediment samples from cores and samples of injection water and ground water. Bacterial densities in water samples also were measured periodically.

(5) Sorption of THMs to aquifer sediments: The potential for sorption of THMs to aquifer sediments was investigated in laboratory experiments using sediment samples from cores.

Site Description

The injection, storage, and recovery demonstration site is located in the Antelope Valley near the city of Lancaster, California (fig. 1). Antelope Valley is a topographically closed basin at the western end of the Mojave Desert; it is subdivided into 12 ground-water subbasins bounded by faults and bedrock outcrops (Bloyd, 1967; Carlson and others, 1998). The three injection, storage, and recovery tests occurred in the Lancaster subbasin at the LACDPW's Avenue L and 5th Street West well field in Lancaster (fig. 2).

The Lancaster subbasin contains alluvial and lacustrine deposits, which are locally as much as 5,000 ft thick (Mabey, 1960; Dibblee, 1967; Londquist and others, 1993). The alluvial deposits consist of interbedded heterogeneous mixtures of silt, sand, and gravel (Dutcher and Worts, 1963; Bloyd, 1967); the lacustrine deposits primarily consist of thick layers of clay, interbedded with thinner sand and silty sand layers (Dibblee, 1967). Stratigraphic, hydrologic, and water-quality data were used to divide the deposits into three aquifers: an upper, a middle, and a lower aquifer (David Leighton, U.S. Geological Survey, written commun., 2000). At the injection, storage, and recovery demonstration site, the upper aquifer extends from the water table to a depth of about 510 ft below land surface, the middle aquifer extends from about 510 to about 730 ft below land surface, and the lower aquifer extends from about 870 ft below land surface to the bedrock (fig. 2). Ground-water flow in the upper aquifer is unconfined, flow in the middle aquifer is unconfined to partially confined at depth, and flow in the lower aquifer is confined by the lacustrine deposit that separates the middle and lower aquifers.

Two wells were used during the third injection, storage, and recovery cycle: wells 7N/12W-27P2 (well 4-32) and 7N/12W-27P3 (well 4-34) (fig. 2; table 1). [The local names for the injection and extraction wells (in parentheses above) are used for the convenience of readers more familiar with these names.] Wells 4-32 and 4-34 penetrate the upper and middle aquifers and are screened from 282 to 717 ft and 280 to 710 ft below land surface, respectively (fig. 2). Well 4-34 is about 180 ft west of well 4-32. During the third cycle, only well 4-32 was used for injection. The experiment was designed to use only well 4-32 for extraction. Unfortunately, during the extraction phase of the cycle, the pump for well 4-32 failed; LACDPW then extracted water from well 4-34 to meet water demand. Data for samples collected and analyzed by LACDPW from well 4-34 during the third cycle are reported in Los Angeles County Department of Public Works (2000). No samples were collected from well 4-34 for analysis by the USGS.

In February 1998, a set of four nested piezometers, 7N/12W-27P5–8, was installed in a borehole about 80 ft east-northeast of well 4-32 (fig. 2, table 1). (The local names for the piezometers are not used in this report.) Borehole geophysical logs were used to determine the most suitable depths for the screened interval for each piezometer (Metzger and others, 2002). The piezometers were screened at depths of 330–370 ft (27P8), 440–460 ft (27P7), 540–560 ft (27P6), and 890–910 ft (27P5) below land surface (fig. 2). The deepest piezometer, 27P5, was placed in the lower aquifer and was not used for this project. A well-bore velocity log completed at well 4-32 under pumping conditions showed that most of the water extracted from the well came from a high flow zone at about 460 to 510 ft below land surface (Steven Phillips, U.S. Geological Survey, written commun., 2001). Piezometer 27P6 was installed in the upper part of the middle aquifer, and piezometer 27P7 was installed in the lower part of the upper aquifer at the approximate depth of the maximum flow zone in well 4-32 (fig. 2). Piezometer 27P8 was installed near the water table.

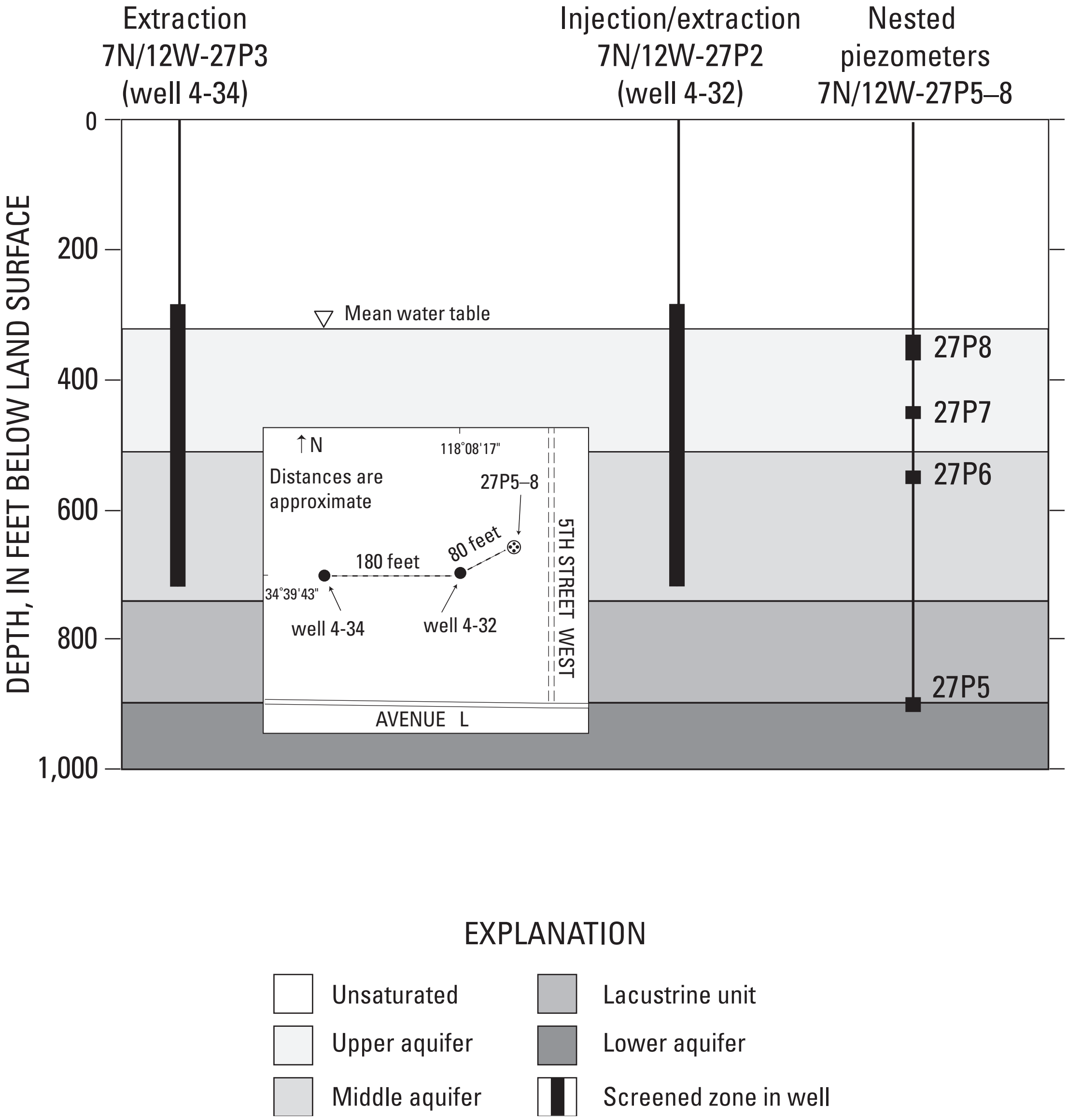

Figure 2. Generalized subsurface geology and locations of wells and nested piezometers at the injection, storage, and recovery test site at Lancaster, Antelope Valley, California. Wells and nested piezometers used during the third cycle (March 1998 through April 1999) are identified by their state names; the wells are also identified by their local names. The inset map shows the relative locations of the wells and piezometers in the Los Angeles County Department of Public Works well field near the corner of Fifth Street and Avenue L.

The water-table fluctuated during the injection, storage, and recovery cycles; for example, the water-table in piezometer 27P6 ranged from 292 ft below land surface in mid-May 1998 (during the injection period) to 357 ft below land surface in mid-August 1998 (during the extraction period) (Metzger and others, 2002).

Sediment cores were collected during the installation of the nested piezometers (fig. 2); the cores were collected from depths approximately corresponding to the depths of the screened intervals for piezometers 27P8, 27P7, and 27P6 (fig. 2). Core recovery was nearly continuous. Table 2 gives detailed descriptions of the cores. All three intervals consisted predominantly of arkosic sand layers interbedded with layers of small gravel and layers of fine sand and silt. Sand and gravel generally were angular and minerals were unweathered, indicating minimal sedimentary processing. Some of the finer grained layers contained discrete black flecks of organic material (less than 1 percent of the layer volume), but overall the sediments contained very little organic material. The ubiquitous reddish colors indicated that all the sediments were oxidized. The sediments were uncemented except in a few zones that contain nodules and layers of caliche (calcium carbonate cement often formed in near-surface sediments in arid environments). The cores were subsampled to provide material for the sorption and the biodegradation studies and the paleomagnetic analyses (table 2).

The age of the upper and middle aquifer was determined by paleomagnetic analyses of core samples. John Hillhouse, USGS Menlo Park, collected oriented samples of fine grained sediments within the cores and analyzed them using alternating field demagnetization. The data showed a change from normal polarity at 344 ft below land surface to reversed polarity at 450 ft below land surface (table 3), which is interpreted as the transition from the Brunhes to the Matayama polarity chron (780,000 years ago; Cande and Kent, 1995). Assuming a constant sedimentation rate, these results indicate that all the sediments in the upper and middle aquifers were deposited since the middle Pleistocene.

Injection and Extraction Chronology for the Third Cycle

For all three cycles, the water used for injection into the wells was imported from the SWP (fig. 1). Existing AVEK pipelines conveyed water from the SWP to the West Quartz Hill Water Treatment Plant where it was treated with chlorine. This treated water was then transported in LACDPW and AVEK pipelines to well 4-32.

During the injection periods of the first and second cycles (1996 and 1997), the water delivered by the SWP originated from the Sacramento–San Joaquin Delta and was conveyed by the Harvey O. Banks pumping plant and the SWP's California Aqueduct (fig. 1). During the injection period of the third cycle (1998), however, the northern segment of the Aqueduct was closed for maintenance, and the water delivered from the SWP originated from Lake Isabella and the Kern River (fig. 1). This source water was compositionally different from the Delta water used during the first two cycles and resulted in some differences in the water-quality patterns observed in the third cycle in comparison with the first two cycles.

Table 1. Nomenclature for wells used during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

State well number 7N/12W-	Local well number	USGS location identification number	Aquifer zone screened	Use of well
27P5	5K8-PZ1	344005118082201	Lower	Not used
27P6	5K8-PZ2	344005118082202	Middle	Piezometer
27P7	5K8-PZ3	344005118082203	Upper	Piezometer
27P8	5K8-PZ4	344005118082204	Upper	Piezometer
27H3	4-33	344008118074701	Upper and middle	Extraction
27J4	4-13	344002118074701	Upper and middle	Extraction
27J6	4-42	344003118074901	Upper, middle, and lower	Extraction
27P2	4-32	343943118081801	Upper and middle	Injection and extraction
27P3	4-34	343943118082101	Upper and middle	Extraction

Table 2. Description of cores from borehole drilled in February 1998 for installation of nested piezometers 7N/12W-27P5–8 at the injection, storage, and recovery test site in Lancaster, Antelope Valley, California

[Colors determined on damp cores using a Munsell color chart (Munsell Color, 1975). Depth, in feet below land surface. ft, foot; in., inch]

Depth, in feet		Core description
From	To	
		Core corresponding approximately to the screened interval for piezometer 7N/12W-27P8. Core interval depth, 330–345.6 ft below land surface; 97-percent recovery.
330.0	331.1	Silty, fine-grained, lithic, moderate orange-brown (7.5YR 4/6) sand. Silt content increases towards top.
331.1	335.9	Poorly sorted, fine- to medium-grained, lithic sand containing occasional angular to subround 0.4-in.-diameter lithic fragments. Sample taken at a depth of 334.5 ft for paleomagnetic analysis.
335.9	338.9	Medium- to coarse-grained, lithic, moderate yellowish-brown (10YR 5/4) sand.
338.9	341.0	Medium- to fine-grained, lithic, moderate yellowish-brown (10YR 5/4) sand.
341.0	344.1	Sandy, moderate orange-brown (7.5YR 4/3 to 4/4) silt. Streaks of organic matter at 342.4–343.5 ft. Streaks are black horizontal flecks and strings 0.04–0.4 in. long and comprise less than 1 percent, by volume, of sediment. Sample taken at a depth of 341.8 ft for paleomagnetic analysis.
344.1	344.6	Silty, moderate orange-brown (7.5YR 4/4) clay with fine lamination that is defined by black flecks of organic matter. Sample taken at a depth of 344.3 ft for paleomagnetic analysis.
344.6	345.6	Poorly sorted, fine-grained, moderate orange-brown (7.5YR 4/4), lithic sand containing 0.08–0.6-in. diameter lithic fragments.
		Core corresponding approximately to the screened interval for piezometer 7N/12W-27P7. Core interval depth, 450–466.5 ft below land surface; 72-percent recovery.
450.0	451.5	Poorly sorted, fine-grained, moderate orange-brown (7.5YR 4/4), lithic sand containing occasional 0.1–0.2 in. diameter lithic fragments. This layer has a sharp lower boundary. Sample taken at a depth of 451.0 ft for paleomagnetic analysis.
451.5	453.5	Gradation from fine-grained, pale orange-brown (7.5YR 6/2) sand and silt at the top to fine- to medium-grained sand at the base of the layer. The layer is cemented by carbonate between depths of 451.6 and 452.7 ft and contains occasional flecks of black organic matter and subround to subangular lithic fragments 0.4 in. in diameter.
453.5	455.1	Coarse-grained, lithic sand that contains a 2-in.-thick layer of gravel at a depth of 454.7 ft.
455.1	455.6	Gradation from fine-grained sand and silt at the top to coarse-grained, lithic sand and gravel at the base of the layer. There is a carbonate-cemented nodule at a depth of 455.3 ft.
455.6	460.0	This portion of the core was not recovered.
460.0	463.1	Fine-grained, moderate orange-brown (7.5YR 5/4) sand and silt that is mottled with moderate reddish-brown (5YR 4/6) patches. The siltier portions contain less than 1 percent, by volume, black flecks of organic material, including several 1-in.-long, relict plant fragments, at a depth of 451.3 ft. Sample taken for paleomagnetic analysis at a depth of 460.5 ft. Sample taken at a depth between 460.8 and 462.5 ft for use in biodegradation experiments.
463.1	463.7	Very poorly sorted fine- to coarse-grained, moderate orange-brown (7.5YR 5/3) sand that contains 20 percent, by volume, lithic fragments that are up to 2 in. in diameter.

Table 2. Description of cores from borehole drilled in February 1998 for installation of nested piezometers 7N/12W-27P5–8 at the injection, storage, and recovery test site in Lancaster, Antelope Valley, California—Continued

Depth, in feet		Core description
From	To	
		Core corresponding approximately to the screened interval for piezometer 7N/12W-27P7. Core interval depth, 450–466.5 ft below land surface; 72-percent recovery—Continued.
463.7	464.3	Fine-grained, moderate orange-brown (7.5YR 5/4) sand and silt that is mottled with moderate reddish-brown (5YR 4/6) patches. The siltier portions contain less than 1 percent, by volume, black flecks of organic material.
464.3	465.6	This layer consists of four sublayers that are separated by sharp boundaries: very poorly sorted, coarse-grained sand and gravel, medium-grained, moderate yellowish-brown (10YR 5/6) sand, coarse-grained sand, and medium-grained, moderate yellowish-brown (10YR 5/4) sand.
465.6	466.5	Poorly sorted, coarse-grained, moderate yellowish-brown (10YR 5/3) lithic sand that contains 10 percent by, volume, angular lithic fragments that are 0.2–0.4 in. in diameter. Matrix sand is faintly banded by grain-size gradation.
		Core corresponding approximately to the screened interval for piezometer 7N/12W-27P6. Core interval depth, 540–549.5 ft below land surface; 100-percent recovery.
540.0	541.0	Fine-grained, moderate yellowish-brown (10YR 4/4) sand with a few whitish patches and a sharp basal boundary defined by a 2-in.-thick clay layer.
541.0	543.0	Sandy, moderate orange-brown (7.5YR 4/4) silt showing faint horizontal banding and containing less than 5 percent by, volume, patches of white clay, and less than 1 percent , by volume, black flecks of organic matter. Interval from 542.0 to 543.0 ft also contains less than 5 percent , by volume, 0.1– 0.2-in.-diameter gravel. Sample taken at a depth of 543.1 ft for paleomagnetic analysis. Sample taken at a depth between 542.5 and 542.9 ft for sorption experiments.
543.0	545.5	Upper half of layer is pale yellowish-gray (10YR 7/2) silt that is cemented by carbonate. Lower half of layer is sandy, moderate yellowish-brown (10YR 5/4) silt that is partially cemented by pale yellowish-gray (10YR 7/2) carbonate in patches and horizontal bands, and also contains occasional flecks of black organic matter.
545.5	548.0	This layer contains five sub-layers, each approximately 0.5 ft thick, that have gradational boundaries: (1) very poorly sorted lithic sand and gravel; (2) sandy, moderate orange-brown (7.5 YR 4/4) silt; (3) very poorly sorted, fine- to medium-grained sand that contains 10 percent , by volume, subangular, 0.2–0.8-in. diameter, lithic fragments; (4) very poorly sorted, coarse-grained, lithic sand and gravel up to 1 in. in diameter; (5) poorly sorted, fine- to medium-grained sand with less than 1 percent , by volume, flecks of black organic matter that contains 10 percent, by volume, angular lithic fragments.
548.0	549.0	Poorly sorted, silty, fine- to medium-grained, moderate orange-brown (7.5YR 4/4) sand that contains sparse flecks of black organic matter. Sample taken at a depth of 548.7 ft for paleomagnetic analysis.
549.0	549.5	Very poorly sorted, lithic, medium-grained sand and 0.1–0.4-in. diameter, angular to subround fragments of quartz, feldspar, biotite-quartz-feldspar gneiss, diorite, and fine-grained black schist.

Table 3. Paleomagnetic data for sediment samples from cores from borehole drilled in February 1998 for installation of nested piezometers 7N/12W-27P6–8 in Lancaster, Antelope Valley, California

[Samples analyzed at the U.S. Geological Survey laboratory at Menlo Park, California. See table 2 for sample locations in cores. mT, millitesla]

Depth below land surface (feet)	Inclination (degrees)	Polarity	Treatment (mT)
333	53.5	Normal	15–40
341	52.2	Normal	15–40
344	55.8	Normal	20–40
450	–53.6	Reversed	15–40
460	47.9	Normal	10–20
543	–20.7	Reversed	10–20
548	66.9	Normal	10–20

Injection at well 4-32 for the third cycle began April 15, 1998, and continued through June 16, 1998 (fig. 3). Water flow into the wellhead was maintained between 700 and 800 gal/min (gallons per minute) except during a brief hiatus for mechanical difficulties at the end of April (Metzger and others, 2002). From the well, the injected water moved into the aquifer by gravity flow. The total volume of water injected was 58 million gallons (fig. 3). Immediately after injection ceased on June 16, 1998, the pump was tested to prepare for the extraction period at which time water-quality samples were collected. The injection period was followed by 2 weeks of water storage in the aquifer during which time no pumping occurred.

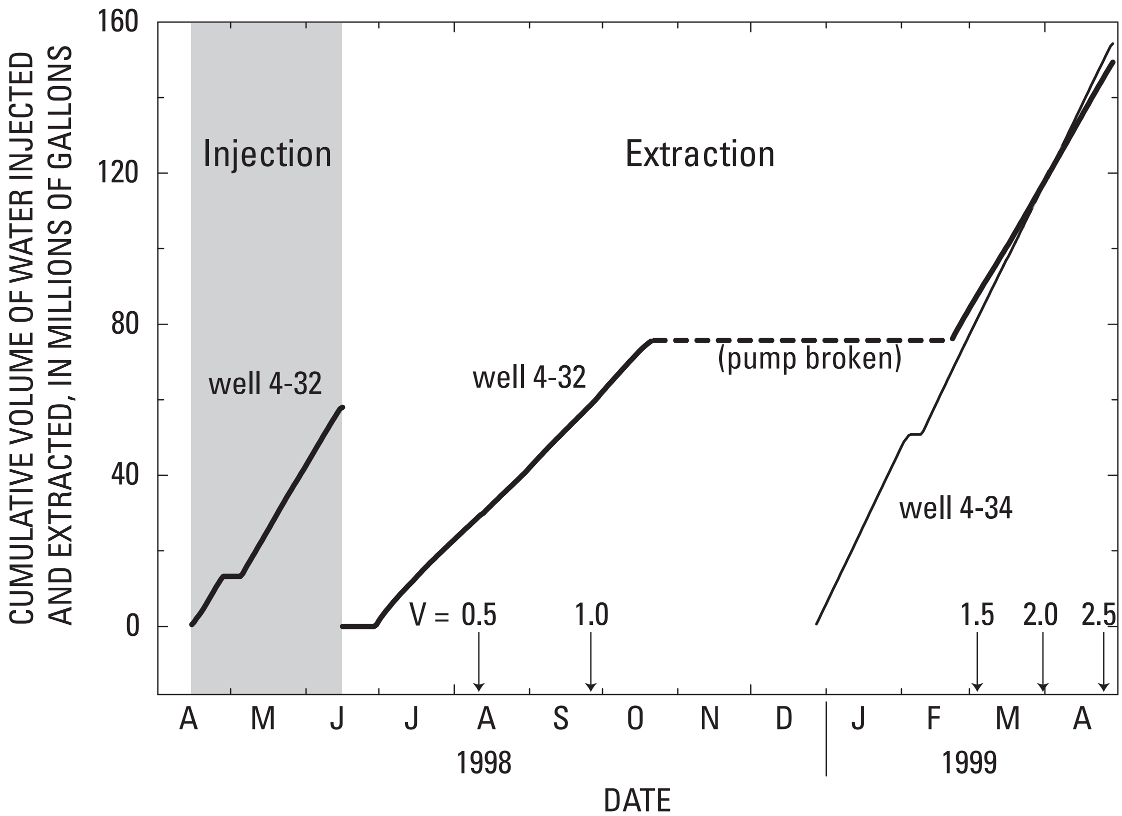

Figure 3. Cumulative volumes of water injected and extracted at 7N/12W-27P2 (well 4-32) and 7N/12W-27P3 (well 4-34) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California. V is the equivalent volume fraction extracted from well 4-32 and is defined as the cumulative volume of water extracted divided by the total volume of water injected. Data are from Metzger and others (2002).

Extraction from well 4-32 began June 30, 1998, and ended April 29, 1999 (fig. 3). No extraction occurred between October 24, 1998, and February 22, 1999, owing to failure and replacement of the pump. Water flow was maintained at 400–550 gal/min during the first phase of extraction (before pump failure) and at 750–800 gal/min during the second phase (after replacement of the pump) (Metzger and others, 2002). The low flow rates during the first phase may have been due to the extremely low water table during that period (Steven Phillips, U.S. Geological Survey, oral commun., 1999). The total volume of water extracted from well 4-32 was 150 million gallons, which was more than 2.5 times the volume injected (fig. 3). The extracted water was blended with other water and incorporated into the LACDPW water distribution system.

After the well 4-32 pump failed, water was extracted from nearby well 4-34 to meet water demand. Extraction from well 4-34 began December 28, 1998, and continued through April 29, 1999. Water flow was maintained at 900–950 gal/min (Loren Metzger, U.S. Geological Survey, written commun., 2000). The total volume of water extracted from well 4-34 was 155 million gallons, which was more than 2.5 times the volume of water injected into well 4-32 (fig. 3).

Acknowledgments

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WATER-QUALITY MONITORING AT WELLS

Water samples were collected from well 4-32 and the nested piezometers and analyzed for a number of water-quality parameters. In addition, replicate samples were collected and analyzed to assess the precision of the analytical methods. The following sections describe the water sampling methods; the statistical method used to calculate analytical precision from the results of replicate analyses; and the methods used by the USGS to analyze residual chlorine, DOC, and THM concentrations, and ultraviolet (UV) absorbance spectra. Analytical precision was calculated for each analytical method.

Sampling Methods

On March 3–6, 1998, approximately 1,000 liters of water was collected during a test of the pump on well 4-32. This water represented the composition of the ground water near well 4-32 prior to the third cycle. The water was collected from a sampling port installed on the horizontal part of the pipe about 3 ft from the vertical drop into the well. The sampling spigot was opened and water was allowed to run several minutes before collection to assure complete flushing of the lines. The water was collected in 10-gallon stainless-steel cans and then pumped through a 0.4-μm (micrometer) pore-size flow-through filter using a peristaltic pump to another set of cans. The cans had been washed with clean deionized water and rinsed three times with sample water prior to filling. The cans were then sealed with tightly fitting stainless-steel lids and transported by truck to the USGS laboratory in Sacramento.

During both the injection and extraction periods, water samples for the USGS were collected from the sampling port on well 4-32. Water was collected in clean, 59-mL (milliliter) amber glass serum vials filled to the top with no headspace and sealed with Teflon-faced septa and aluminum crimp tops. Ten vials of water were collected for each sampling of injection water, and five vials were collected for each sampling of extraction water. The vials were packed on ice and shipped overnight to the USGS laboratory in Sacramento for use in laboratory experiments and for analysis of THM, DOC, and residual chlorine concentrations and ultraviolet absorbance (UVA) spectra.

LACDPW and AVEK collected samples during the injection and extraction periods from the same sampling port for analysis by their respective laboratories (Metzger and others, 2002). Samples for THM analysis were collected headspace-free in glass vials with Teflon-faced septa and screw-caps, and spiked with sodium sulfite to quench the remaining residual chlorine. Temperature, pH, conductivity, turbidity, and free and total residual chlorine were measured on site using standard methods (table 4), and concentrations of dissolved constituents were analyzed by LACDPW and AVEK (table 4).

Table 4. Standard analytical methods used by cooperating agencies during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[AVEK, Antelope Valley–East Kern Water Agency; EPA, U.S. Environmental Protection Agency; LACDPW, Los Angeles County Department of Public Works; SM, from "Standard Methods for the Examination of Water and Wastewater" (American Public Health Association, 1995)]

Analyte	Agency	Method
Trihalomethanes	AVEK	EPA 502.2: Purge and trap gas chromatography–electron-capture detector
Trihalomethanes	LACDPW	EPA 524.2: Gas chromatography–mass spectrometry
Conductivity	AVEK	SM 2510 B: Conductivity
Conductivity	LACDPW	SM 2510 B: Conductivity
pH	AVEK	SM 4500-H+ B: Electrometric method
pH	LACDPW	SM 4500-H+ B: Electrometric method
Temperature	LACDPW	SM 2550 B: Temperature
Turbidity	AVEK	SM 2130 B: Nephelometric method
Turbidity	LACDPW	SM 2130 B: Nephelometric method
Residual chlorine	AVEK	SM 4500-Cl G: DPD colorimetric method
Residual chlorine	LACDPW	SM 4500-Cl G: DPD colorimetric method
Dissolved solids	LACDPW	SM 2540 C: Dissolved solids dried at 180 degrees Celsius
Chloride	AVEK	EPA 300.0 A: Suppression ion chromatography
Chloride	LACDPW	SM 4110 B: Ion chromatography with chemical suppression of eluant conductivity
Bromide	AVEK	EPA 300.0 A: Suppression ion chromatography
Nitrate	LACDPW	SM 4110 B: Ion chromatography with chemical suppression of eluant conductivity
Sulfate	LACDPW	SM 4110 B: Ion chromatography with chemical suppression of eluant conductivity

During the injection period, the time interval at which samples were collected from well 4-32 varied. LACDPW and AVEK collected and analyzed water samples once per week (on different days) throughout the injection period and sent duplicate samples to the USGS laboratory in Sacramento. The USGS analyzed four samples per week during the injection period: the duplicate samples sent by LACDPW and AVEK and the samples collected by LACDPW personnel on two additional days.

The 10 vials of water collected during each sampling of injection water were processed in the following manner immediately upon arrival at the USGS Sacramento laboratory.

Vial 1: This first vial was opened and the sample was measured for free and total residual chlorine. The remainder of this sample was poured into a smaller vial, resealed headspace-free, and spiked with sodium sulfite to quench the residual chlorine.

Vial 2: This second vial also was spiked with sodium sulfite to quench the residual chlorine. THM concentrations were measured in the two quenched vials.

Vials 3–6: The contents of these four vials were combined and filtered. Then the sample was filtered by gravity filtration in either a stainless steel or a Teflon, 47-millimeter-diameter filtration tower through a 0.3-µm (micrometer) pore size, glass fiber filter. The filters were precombusted at 450ºC for 4 hours. The filtration towers were cleaned with ultra-high-purity clean water between samples and preconditioned by filtering approximately 25 mL of sample to waste before collecting the filtered water. Approximately 75 mL of filtered water was collected for analysis of DOC concentration and the UVA spectrum. The remaining 125 mL of filtered water was sparged for 30 minutes with ultra-high-purity nitrogen gas to remove the THMs and then spiked with sodium sulfite to quench the residual free chlorine. The filtered, sparged, quenched water was used in the THMFP experiments.

Vials 7–10: These remaining four vials were stored in a 25ºC incubator for different periods of time for the storage experiment. If fewer than ten vials arrived, due to breakage during transit, or if a vial contained significant headspace gas, then fewer than four vials were used for the storage experiment.

During the extraction period, AVEK collected and analyzed samples once a week. LACDPW collected and analyzed samples daily for the first two weeks of extraction and then weekly for the rest of the extraction period (again, on a different day than did AVEK). Sample collection by LACDPW personnel for the USGS did not begin until the third week of extraction. The USGS then analyzed these samples weekly.

The nested piezometers were sampled eight times during the third cycle. A submersible pump was used to extract water samples from piezometers 7N/12W-27P6–8. Prior to collecting the water sample, the well and piezometer casings were purged of standing water by pumping at least three casing volumes of water. Water samples were collected in clean, 59-mL amber glass serum vials filled to the top with no headspace and sealed with Teflon-faced septa and aluminum crimp tops.

Five vials of water were collected during each sampling of extraction water and piezometer water, and were processed as follows in the USGS Sacramento laboratory.

Vials 1 and 2: These two vials were used for measurement of THM concentrations. The extraction and piezometer water samples did not contain measurable residual chlorine upon arrival in Sacramento; therefore, it was not necessary to quench the samples.

Vials 3–5: The contents of these three vials were combined and filtered (as described previously for the injection water in vials 3–6) for analysis of DOC concentration and UVA spectrum.

Statistical Method for Assessment of Quality-Control Data

Replicate analyses were done on many samples to asses the precision of the analytical methods. A mathematical expression for analytical precision was derived using statistical formulations from Helsel and Hirsch (1995) and Kenkel (1992). Analytical precision for each method was calculated by combining the results of replicate analyses of many samples. The deviation between results of replicate analyses of one sample is described by the percent relative standard deviation (RSD) which is calculated from the mean and the standard deviation of the replicate analyses:

$$RSD = \frac{s_x}{x} \times 100 ,$$

$$\text{where } s_x = \sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}}$$

$$\text{and} \quad \bar{x} = \frac{\sum x}{n}$$

and where

x is the value for an analysis,

n is the number of replicate analyses,

$\bar{x}$ is the mean of the replicate analyses,

s_x is the standard deviation of the replicate analyses, and

RSD is the relative percent standard deviation for the replicate analyses.

RSD, rather than the mean of the differences between replicate analyses, was used because the precision implied by absolute differences between replicate analyses changes with the magnitude of the measured value. Using RSD normalizes the magnitude of the error to that of the measured value and, therefore, provides a consistent indicator of precision over a wide concentration range.

The RSDs for all the individual samples were then combined to determine the standard deviation (s_{RSD}) and the mean RSD ($\overline{\text{RSD}}$):

$$s_{RSD} = \sqrt{\frac{\sum (RSD - \overline{RSD})^2}{N}} ,$$

$$\text{where} \quad \overline{RSD} = \frac{\sum RSD}{N}$$

and where

N is the number of samples,

s_{RSD} is the standard deviation of the *RSDs*, and

$\overline{RSD}$ is the mean of the *RSD*s.

The width of the 95-percent confidence interval about $\overline{\text{RSD}}$ was calculated using the Student's *t*, the probability factor associated with the 95-percent confidence level and *N* samples:

$$\text{interval width} = \pm \frac{t \times s_{RSD}}{N}$$

Analytical precision at the 95-percent confidence level is then $\overline{\text{RSD}}$ plus the absolute value of the interval width.

$$\text{analytical precision} = |\text{interval width}| + \overline{RSD}$$

Adding the interval width to the $\overline{\text{RSD}}$ yields the most conservative estimate of analytical precision.

Analytical Methods

Analytical methods used by the USGS Sacramento laboratory to measure residual chlorine, DOC, and THM concentrations and UVA absorption are discussed in this section. The statistical method just described is used to assess analytical precision for these analytical methods. Methods used by the LACDPW and AVEK laboratories are given in table 4.

Free and Total Residual Chlorine Analysis

Free and total residual chlorine were measured using the HACH DPD colorimetric method (HACH, 1997). Replicate analyses were done on 16 samples to assess analytical precision (table 5). The $\overline{\mathrm{RSD}}$ for the 16 pairs of replicate residual free chlorine measurements was 1.3 percent and the 95-percent confidence interval width was ±0.7 percent. The $\overline{\mathrm{RSD}}$ for the 16 pairs of replicate total residual chlorine measurements was 0.5 percent, and the 95-percent confidence interval width was ±0.3 percent. Thus, the analytical precision was 2.0 percent for the free chlorine measurement and 0.8 percent for the total chlorine measurement.

Free and total residual chlorine concentrations measured in the USGS Sacramento laboratory could not be compared with those measured on the same samples on site by LACDPW and AVEK. During the 1-day transit from Lancaster to Sacramento, the chlorine in the samples continued to react with the DOC, and therefore the USGS values were always lower than the LACDPW and AVEK values for the same samples. Also, total residual chlorine measurements made by LACDPW and AVEK could not be compared because the two agencies collected samples on different days.

Ultraviolet Absorption Analysis

Ultraviolet absorbance (UVA) measurements were made with a Perkin-Elmer Lambda 3B

Table 5. Quality-assurance and quality-control data for free and total residual chlorine analyses done by the U.S. Geological Survey during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Analytical precision was calculated from results for replicate analyses of 16 samples. Percent relative standard deviation (RSD) was calculated for each sample. The mean RSD ($\overline{\mathrm{RSD}}$) and the width of the 95-percent confidence interval about the $\overline{\mathrm{RSD}}$ then were calculated. Method analytical precision is the $\overline{\mathrm{RSD}}$ plus the absolute value of the confidence interval width. See p. 12 in text for further explanation. Samples were collected from well 7N/12W-27P2 (well 4-32) during the injection period of the cycle. mg/L, milligram per liter]

Sampling date	Replicate analyses of residual free chlorine (mg/L)		RSD	Replicate analyses of total residual chlorine (mg/L)		RSD
	Run 1	Run 2		Run 1	Run 2	
04/15/98	0.82	0.76	5.12	0.98	0.97	1.10
04/16/98	.53	.53	.69	.65	.65	.55
04/17/98	.60	.60	.61	.72	.71	1.00
04/18/98	.85	.81	3.09	.92	.93	.39
04/19/98	.89	.87	2.08	1.01	1.01	.00
04/20/98	.95	.97	1.52	1.09	1.09	.00
04/22/98	.74	.76	1.46	.86	.87	.41
04/23/98	.51	.50	.73	.62	.64	2.28
05/26/98	.73	.72	.51	.85	.85	.42
05/27/98	.97	.96	.76	1.07	1.06	1.00
05/28/98	.98	.98	.00	1.06	1.06	.00
06/02/98	1.11	1.09	1.33	1.21	1.20	.59
06/03/98	1.33	1.33	.28	1.42	1.42	.00
06/04/98	.77	.77	.00	.88	.88	.41
06/08/98	.52	.53	1.41	.61	.61	.00
06/15/98	.84	.85	1.30	.91	.91	.00
Mean relative standard deviation, $\overline{\mathrm{RSD}}$, in percent			1.3			0.5
95-percent confidence interval width, in percent			±.7			±.3
Method analytical precision, in percent			±2.0			±.8

spectrophotometer using a modified version of Standard Method 5910B (American Public Health Association, 1995). UVA was measured at 254 nm (nanometer) (UVA_{254}) and across a full scan from 310 to 195 nm. All measurements were made within 1 week of sample collection. Replicate analyses were done on 10 samples to assess analytical precision (table 6). The $\overline{RSD}$ for the 10 pairs of replicate measurements of UVA_{254} was 0.04 percent and the 95-percent confidence interval width was ±0.09 percent, giving an analytical precision of 0.13 percent. This high degree of precision reflects the fact that the replicate measurements were identical for 9 of the 10 samples.

Table 6. Quality-assurance and quality-control data for ultraviolet absorption analyses done by the U.S. Geological Survey during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Analytical precision was calculated from results for replicate analyses of 10 samples. Percent relative standard deviation (RSD) was calculated for each sample. The mean RSD ($\overline{RSD}$) and the width of the 95-percent confidence interval about the $\overline{RSD}$ were then calculated. Method analytical precision is the $\overline{RSD}$ plus the absolute value of the confidence interval width. See p. 12 in text for further explanation. Injection, extraction, and ground-water samples were collected from well 7N/12W-27P2 (well 4-32). Piezometer samples were collected from nested piezometers 7N/12W-27P6–8. UVA_{254}, ultraviolet absorbance at 254 nanometers]

Sampling date	Sample type	Replicate analyses of UVA_{254}		RSD
		Run 1	Run 2	
02/18/1998	Piezometer (27P6)	0.005	0.005	0.00
03/06/1998	Ground water	.004	.004	.00
03/12/1998	Piezometer (27P6)	.003	.003	.00
04/18/1998	Injection	.030	.030	.00
06/15/1998	Injection	.019	.019	.00
08/04/1998	Piezometer (27P8)	.299	.299	.00
10/07/1998	Extraction	.008	.008	.00
11/05/1998	Piezometer (27P8)	.169	.168	.42
03/24/1999	Extraction	.007	.007	.00
04/07/1999	Extraction	.012	.012	.00
Mean relative standard deviation, $\overline{RSD}$, in percent				0.04
95-percent confidence interval width, in percent				±.09
Method analytical precision, in percent				±.13

Dissolved Organic Carbon Analysis

DOC concentrations were measured using a Shimadzu TOC-5000A analyzer with ASI-5000A autosampler following a modified version of Standard Method 5310B (American Public Health Association, 1995). The Shimadzu instrument uses high-temperature catalytic oxidation to convert DOC into carbon dioxide (CO_2), which is then measured using a nondispersive infrared photometric cell. Because all of the samples in this study had low DOC concentrations, the high-sensitivity catalyst was used for all analyses. This catalyst consists of platinum-coated glass wool (rather than the platinum-coated ceramic beads in the normal catalyst) and is designed to analyze samples containing less than 2 mg/L (milligram per liter) DOC. All samples were acidified to pH 2 and purged with carbon-free, purified air just before analysis to remove inorganic carbon. Standard curves were constructed by analyzing solutions of potassium hydrogen phthalate with known DOC concentrations.

Analytical precision for the DOC analyses varied significantly with DOC concentration; errors were much larger for measurements on samples containing mean DOC concentrations of less than 1 mg/L. The $\overline{RSD}$ for the 29 pairs of replicate measurements on samples containing mean DOC concentrations of less than 1 mg/L was 9.4 percent and the 95-percent confidence interval width was ±2.7 percent, giving an analytical precision of 12.1 percent (table 7). The $\overline{RSD}$ for the 34 pairs of replicate measurements on samples with mean DOC concentrations greater than 1 mg/L was 2.5 percent and the 95-percent confidence interval width was ±0.7 percent, giving an analytical precision of 3.2 percent (table 7).

The accuracy of the DOC measurements was assessed by analyzing standards as unknowns. The standards were solutions of potassium hydrogen phthalate with known DOC concentrations. Three standards and one aliquot of blank water were analyzed as unknowns between each set of 10 samples and 2 replicate samples analyzed. Data were accepted only if the measured values of the three standards analyzed

Table 7. Quality-assurance and quality-control data for dissolved organic carbon analyses done by the U.S. Geological Survey during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Analytical precision was calculated from results for replicate analyses of 63 samples. Percent relative standard deviation (RSD) was calculated for each sample. The mean RSD ($\overline{RSD}$) and the width of the 95-percent confidence interval about the $\overline{RSD}$ were then calculated. Method analytical precision is the $\overline{RSD}$ plus the absolute value of the confidence interval width. See p. 12 in text for further explanation. Samples were collected from wells 7N/12W-27P2 (well 4-32), 7N/12W-27H3 (well 4-33), 7N/12W-27J4 (well 4-13), and 7N/12W-27J6 (well 4-42), and nested piezometers 7N/12W-27P6, 27P7, and 27P8. Sample type: GW, ground water; Ext, extraction water; Inj, injection water; —, water from piezometer. Data are sorted in ascending order by mean dissolved organic carbon (DOC) concentration. mg/L, milligram per liter]

Sampling date	Sample type	Data for samples with mean DOC concentration less than 1 mg/L				
		Replicate analyses of DOCs (mg/L)			Mean DOC (mg/L)	RSD
		Run 1	Run 2	Run 3		
10/08/1998	Ext (4-33)	0.154	0.114		0.134	21.11
02/26/1998	— (27P6)	.161	.142		.152	8.87
10/08/1998	Ext (4-13)	.149	.161		.155	5.47
03/06/1998	GW (4-32)	.162	.149		.156	5.91
03/06/1998	GW (4-32)	.177	.135		.156	19.04
03/06/1998	GW (4-32)	.209	.126		.168	35.04
03/12/1998	— (27P7)	.174	.174	0.181	.176	2.29
10/08/1998	Ext (4-42)	.175	.217		.196	15.15
03/06/1998	GW (4-32)	.209	.182	.204	.198	7.24
03/06/1998	GW (4-32)	.205	.235		.220	9.64
03/06/1998	GW (4-32)	.274	.248		.261	7.04
10/07/1998	Ext (4-32)	.283	.264	.264	.270	4.06
10/21/1998	Ext (4-32)	.285	.335		.310	11.40
09/30/1998	Ext (4-32)	.369	.304		.337	13.66
09/16/1998	Ext (4-32)	.353	.353	.390	.365	5.85
09/03/1998	Ext (4-32)	.476	.410		.443	10.53
03/13/1998	— (27P8)	.479	.440		.460	6.00
03/23/1999	GW (27P7)	.688	.607		.648	8.85
08/04/1998	Ext (4-32)	.853	.789	.702	.781	9.70
07/28/1998	Ext (4-32)	.813	.800		.807	1.14
11/05/1998	— (27P7)	.779	.840		.810	5.33
12/03/1998	— (27P6)	.812	.818	.840	.823	1.79
10/07/1998	— (27P7)	.877	.836		.857	3.38
11/05/1998	— (27P8)	.897	.860		.879	2.98
12/02/1998	— (27P7)	.824	.908	1.000	.911	9.67
10/07/1998	— (27P6)	.868	.954		.911	6.68
07/24/1998	Ext (4-32)	.835	.997		.916	12.51
07/22/1998	Ext (4-32)	.884	.951		.918	5.16
10/07/1998	— (27P8)	.834	1.078		.956	18.05

Mean relative standard deviation, $\overline{RSD}$, in percent........ 9.4

95-percent confidence interval width, in percent........ ±2.7

Method analytical precision, in percent........ ±12.1

Table 7. Quality-assurance and quality-control data for dissolved organic carbon analyses done by the U.S. Geological Survey during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster , Antelope Valley, California—Continued

Sampling date	Sample type	Data for samples with mean DOC concentration greater than 1 mg/L					
		Replicate analyses of DOCs (mg/L)				Mean DOC (mg/L)	RSD
		Run 1	Run 2	Run 3	Run 4		
11/05/1998	— (27P6)	0.97	1.05	1.02		1.01	3.72
03/24/1999	Ext (4-32)	1.07	1.05			1.06	1.33
05/14/1998	Inj (4-32)	1.45	1.42	1.48		1.45	2.07
05/18/1998	Inj (4-32)	1.56	1.45	1.42		1.48	4.99
05/20/1998	Inj (4-32)	1.58	1.51	1.54		1.54	2.28
05/19/1998	Inj (4-32)	1.61	1.52	1.54		1.56	3.04
05/13/1998	Inj (4-32)	1.55	1.57			1.56	.91
05/21/1998	Inj (4-32)	1.54	1.57	1.57		1.56	1.11
05/12/1998	Inj (4-32)	1.60	1.59	1.57		1.59	.96
06/16/1998	Inj (4-32)	1.65	1.49	1.54	1.75	1.61	7.23
04/07/1999	Ext (4-32)	1.62	1.68			1.65	2.40
06/03/1998	Inj (4-32)	1.76	1.58			1.67	7.62
03/25/1999	— (27P6)	1.71	1.66	1.63		1.67	2.42
06/04/1998	Inj (4-32)	1.73	1.70	1.70		1.71	1.01
05/28/1998	Inj (4-32)	1.76	1.76			1.76	.00
06/01/1998	Inj (4-32)	1.82	1.71			1.77	4.41
06/11/1998	Inj (4-32)	1.85	1.71			1.78	5.56
06/09/1998	Inj (4-32)	1.84	1.73			1.79	4.36
06/10/1998	Inj (4-32)	1.76	1.81			1.79	1.98
05/27/1998	Inj (4-32)	1.70	1.84	1.85		1.80	4.67
04/21/1998	Inj (4-32)	1.85	1.85	1.83		1.84	.63
04/23/1998	Inj (4-32)	1.88	1.83	1.87		1.86	1.42
04/22/1998	Inj (4-32)	1.92	1.85	1.86		1.88	2.02
04/18/1998	Inj (4-32)	1.91	1.86	1.94	1.81	1.88	3.04
05/07/1998	Inj (4-32)	1.93	1.86			1.90	2.61
04/20/1998	Inj (4-32)	1.89	1.92	1.89		1.90	.91
06/08/1998	Inj (4-32)	1.91	1.90			1.90	.37
04/16/1998	Inj (4-32)	1.98	1.93	1.92		1.94	1.65
04/17/1998	Inj (4-32)	2.07	1.87	1.93		1.96	5.25
04/19/1998	Inj (4-32)	1.98	1.96	1.94		1.96	1.02
05/26/1998	Inj (4-32)	1.99	2.00			2.00	.35
04/15/1998	Inj (4-32)	2.03	2.02	2.01		2.02	.50
03/24/1999	— (27P8)	2.13	2.13			2.13	.00
03/10/1999	Ext (4-32)	2.46	2.40	2.43		2.43	1.34
Mean relative standard deviation, $\overline{RSD}$, in percent							2.5
95-percent confidence interval width, in percent							±.7
Method analytical precision, in percent							±3.2

before and after the set of samples were within ±5 percent of the known values. If the measured concentrations in the standards were out of this range, all samples in the intervening set were reanalyzed.

Trihalomethane Analysis

THM concentrations in water samples were measured by purge and trap gas chromatography using a modified version of EPA method 502.2 (U.S. Environmental Protection Agency, 1995). The analyses were done using a Tekmar LSC2000 concentrator and ALS2016 autosampler coupled to a Hewlett-Packard 5890 II gas chromatograph fitted with an electron-capture detector and a modified split-splitless injector. All four THM species were measured: chloroform ($CHCl_3$), bromodichloromethane ($CHCl_2Br$), dibromochloromethane ($CHClBr_2$), and bromoform ($CHBr_3$). Baseline chromatographic separation was achieved using a 30-m (meter) DB-VRX megabore column. The column oven was programmed to hold its temperature at 30ºC for 1 minute, ramp to 125ºC in three ramps, and then hold at 125ºC for 1 minute for a total oven program of 10 minutes. Efficient purging, trapping, and desorbtion were achieved by purging for 11 minutes with 30 pounds per square inch of ultra-high-purity nitrogen, by using a Tekmar #3 trap, and by desorbing at a temperature of 225ºC. The Tekmar unit was spliced into the carrier gas line of the injector, and the septum purge line was capped.

THM concentrations were quantified using seven-point standard curves constructed with Supelco certified THM standard mixtures. The standard curve spanned concentrations of 1.0–84 µg/L $CHCl_3$, and 0.25–21 µg/L $CHCl_2Br$, $CHClBr_2$, and $CHBr_3$. All injections were spiked with a surrogate compound, 2-bromo-1-chloropropane. Analyses were rejected if surrogate recovery was outside the 10-percent relative standard deviation from the surrogate mean for the run. To monitor accuracy, two standards were analyzed as unknowns. These standards were prepared using Supelco certified THM mixtures; their concentrations corresponded to the lower and upper concentrations of the standard curve. Data were accepted only if the measured values of the standards were within ±10 percent of the known concentrations.

To assess precision of the THM concentration analyses, replicate vials of 33 samples were analyzed (table 8). The $\overline{RSD}$ for the 33 pairs of replicate measurements of total THMs was 5.5 percent and the 95-percent confidence interval width was ±1.8 percent, giving an analytical precision of 7.3 percent. However, the distribution of RSD values was highly skewed.

Table 8. Quality-assurance and quality-control data for trihalomethane analyses done by the U.S. Geological Survey during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Analytical precision was calculated from results for replicate analyses of 33 samples. Percent relative standard deviation (RSD) was calculated for each sample. Then the mean RSD ($\overline{RSD}$) and the width of the 95-percent confidence interval about the $\overline{RSD}$ were calculated. Method analytical precision is the $\overline{RSD}$ plus the absolute value of the confidence interval width. See p. 12 in text for further explanation. Table is sorted by RSD. Injection and extraction samples were collected from well 7N/12W-27P2 (well 4-32). Piezometer samples were collected from nested piezometers 7N/12W-27P6–8. THM, trihalomethane. µg/L, microgram per liter]

Sampling date	Sample type	Total THMs (µg/L)		RSD
		Run 1	Run 2	
08/04/1998	Piezometer (27P7)	63.7	63.7	0.00
05/07/1998	Injection	45.7	45.5	.31
06/16/1998	Piezometer (27P8)	57.3	57.0	.37
09/09/1998	Extraction	18.7	18.8	.38
09/03/1998	Piezometer (27P7)	59.5	58.7	.96
02/24/1998	Extraction	14.5	14.7	.97
08/04/1998	Piezometer (27P6)	56.6	55.8	1.01
04/23/1998	Injection	45.2	44.4	1.26
04/20/1998	Injection	42.6	43.6	1.64
04/16/1998	Injection	44.1	43.0	1.79
06/15/1998	Piezometer (27P6)	58.4	56.6	2.21
12/03/1999	Piezometer (27P6)	40.4	41.7	2.24
04/22/1998	Injection	48.9	47.2	2.50
04/17/1998	Injection	51.5	49.3	3.09
06/11/1998	Injection	40.3	42.6	3.92
04/21/1998	Injection	42.1	44.9	4.55
09/03/1998	Piezometer	31.5	33.6	4.56
09/16/1998	Extraction	16.7	17.9	4.90
10/07/1998	Extraction	15.1	16.2	4.97
07/31/1998	Extraction	41.9	39.0	5.07
09/23/1998	Extraction	17.9	16.6	5.33
05/12/1998	Injection	42.4	39.2	5.55
08/19/1998	Extraction	28.7	26.2	6.44
05/18/1998	Injection	40.0	36.1	7.25
08/07/1998	Extraction	37.6	33.3	8.58
06/16/1998	Extraction	52.2	59.2	8.89
08/21/1998	Extraction	23.4	26.6	9.05
08/17/1998	Extraction	11.8	10.3	9.60
07/24/1998	Extraction	21.6	25.2	10.88
05/14/1998	Injection	38.1	32.1	12.09
03/10/1998	Extraction	7.2	8.9	14.93
05/19/1998	Injection	24.5	30.4	15.20
08/11/1998	Extraction	18.1	24.7	21.81

Mean relative standard deviation, $\overline{RSD}$, in percent	5.5
95-percent confidence interval width, in percent	±1.8
Method analytical precision, in percent	±7.3

The median RSD value for the 33 pairs was 4.6 percent, which implies greater precision than that indicated by the $\overline{RSD}$. This indicates that outliers strongly influenced the statistical analysis. The outliers probably were caused by errors in sample collection rather than by analytical error. In practice, the sample vials rarely were completely headspace-free, and a number of vials were sealed with the septa upside down, allowing volatiles to leak. Five of the samples for which replicate vials were analyzed had an RSD greater than 10 percent (table 8). Such large differences between replicate vials probably reflect problems in sample collection rather than true analytical error.

Comparison of THM concentrations determined by the USGS, LACDPW, and AVEK laboratories showed no systematic differences between the laboratories (fig. 4). Twenty-three of the samples collected during the extraction phase of the cycle were analyzed by two of the three laboratories. However, the average deviation of the points on figure 4 from the 1:1 line (perfect agreement between the labs) was ±13 percent, which was significantly greater than the error associated with replicate analyses at the USGS laboratory. The reason for the greater error is unknown.

Results

Injection Water

Data for samples of injection water collected from well 4-32 are shown in figure 5*A*–*I* and are given in tables 9 and 10. The injection water was fairly uniform in composition and contained low

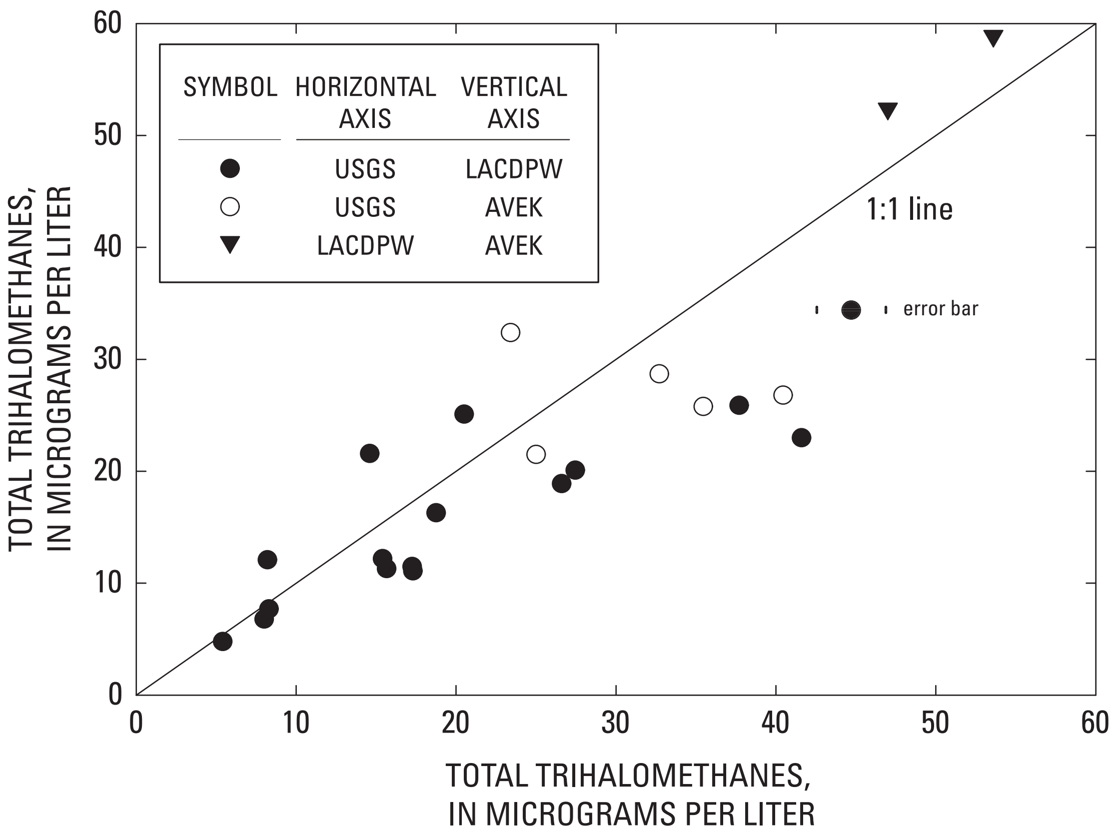

Figure 4. Total trihalomethane (THM) concentrations measured at the U.S. Geological Survey (USGS), the Los Angeles County Department of Public Works (LACDPW), and the Antelope Valley–East Kern Water Agency (AVEK) laboratories for the third injection, storage, and recovery cycle (March 1998 through April 1999). Points represent total THM concentrations measured in replicate samples of extraction water from well 7N/12W-27P2 (well 4-32) that were sent to the different laboratories. Analytical precision for samples measured by the USGS is indicated by the error bar on the point representing the highest concentration, and the size of the error bar decreases as concentration decreases until it is smaller than the size of the points for concentrations below 13 micrograms per liter.

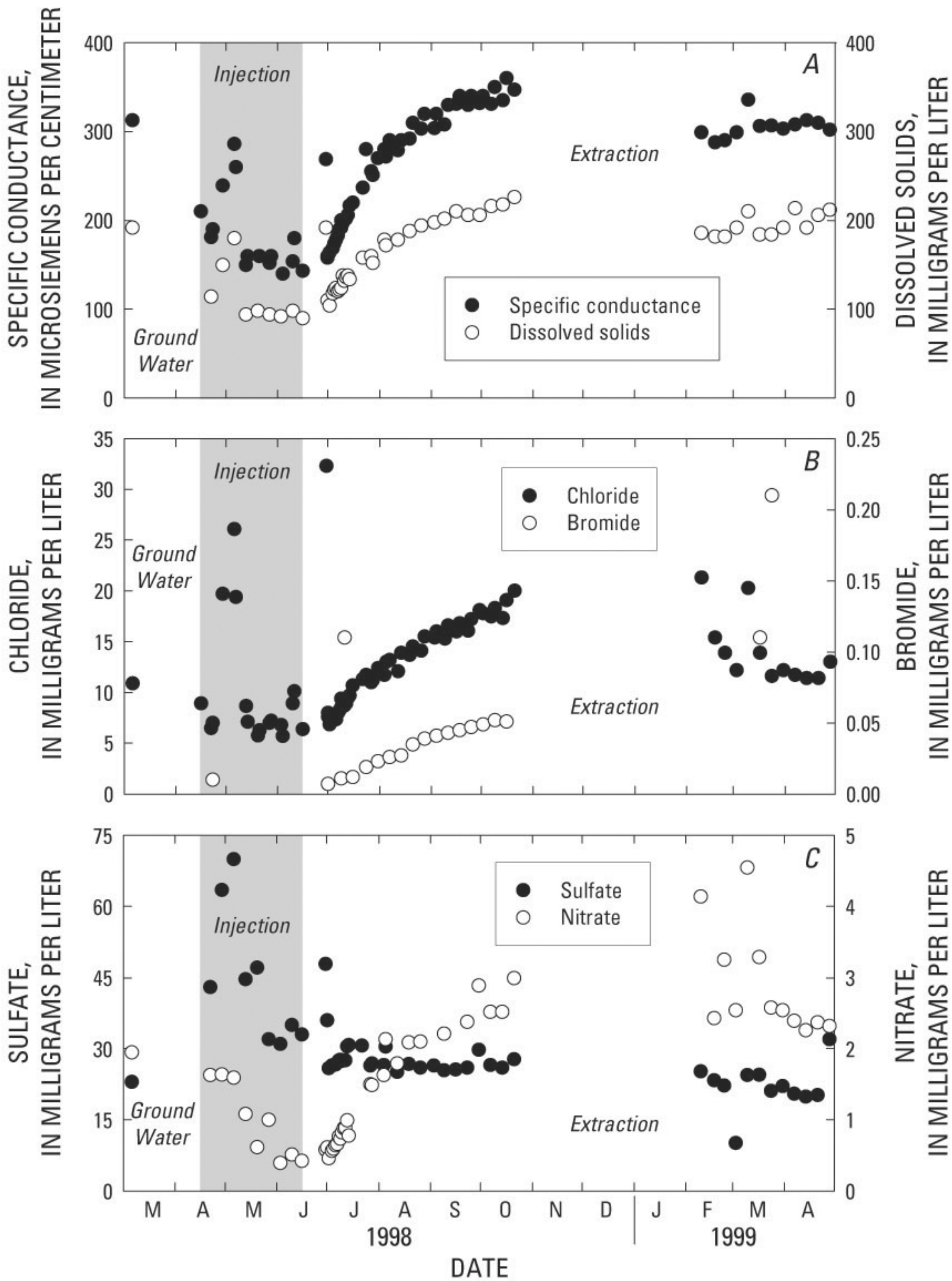

Figure 5*A*–*C*. Concentrations of dissolved species in ground water, injection water, and extraction water collected from well 7N/12W-27P2 (well 4-32) and the nested piezometers 7N/12W-27P6–8 during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California.

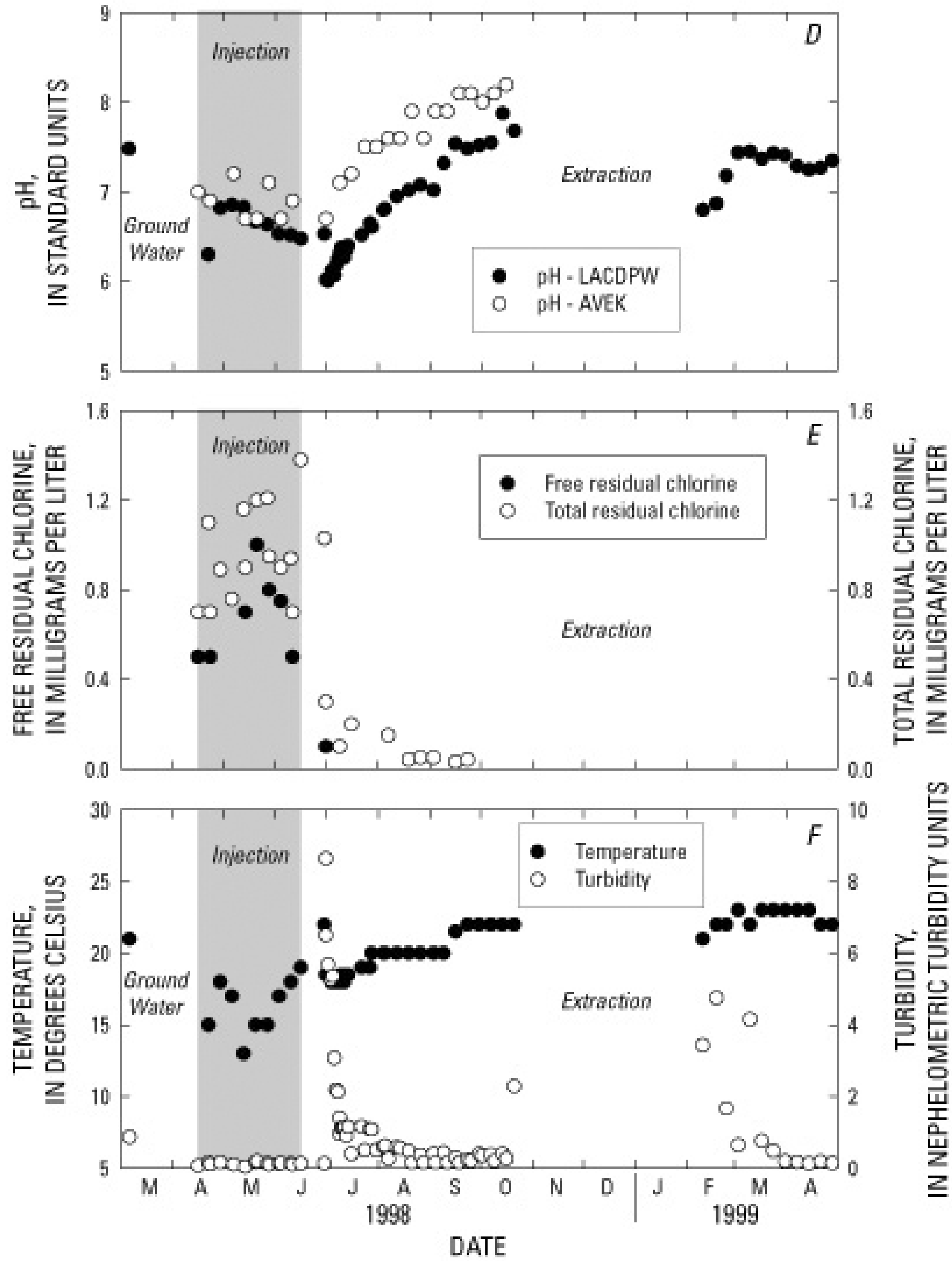

Figure 5*D–F*. Concentrations of dissolved species in ground water, injection water, and extraction water collected from well 7N/12W-27P2 (well 4-32) and the nested piezometers 7N/12W-27P6–8 during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California. LACDPW, Los Angeles County Department of Public Works; AVEK, Antelope Valley–East Kern Water Agency.—Continued

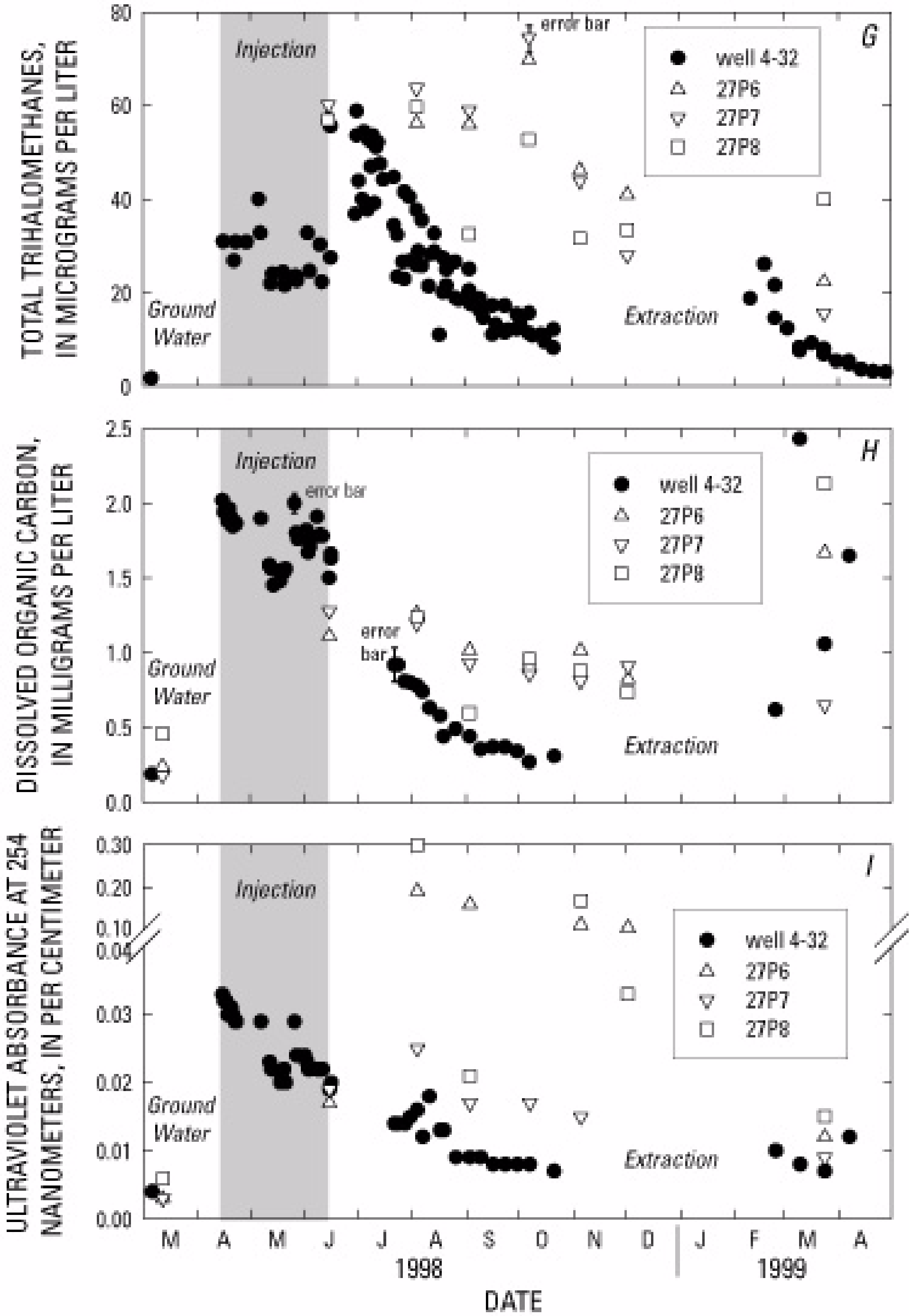

Figure 5*G–I*. Concentrations of dissolved species in ground water, injection water, and extraction water collected from well 7N/12W-27P2 (well 4-32) and the nested piezometers 7N/12W-27P6–8 during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California. The analytical precisions determined in this report for total trihalomethane (THM) concentration, dissolved organic carbon (DOC) concentration greater than 1 mg/L (milligram per liter), DOC concentration less than 1 mg/L, and ultraviolet absorbance at 254 nanometers (UVA_{254}) are applied to the data. An error bar is shown only with the data point representing the highest concentration. The size of the error bar decreases as concentration decreases until it is smaller than the size of the points for concentrations below 34 micrograms per liter for total THMs, below 1.56 mg/L for DOC greater than 1 mg/L, and below 0.4 mg/L for DOC less than 1 mg/L. The error bars are smaller than the points for all of the UVA_{254} data.—Continued

Table 9. Water-quality data for injection water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Samples analyzed at two laboratories: AVEK, Antelope Valley–East Kern Water Agency; LACDPW, Los Angeles County Department of Public Works. Event day, number of days since beginning of injection period. THM, trihalomethane; $CHCl_3$, chloroform; $CHCl_2Br$, bromodichloromethane; $CHClBr_2$, dibromochloromethane; $CHBr_3$, bromoform; N, nitrogen. µg/L, microgram per liter; µS/cm, microsiemen per centimeter; °C, degrees Celsius; NTU, nephelometric turbidity unit; mg/L, milligram per liter; <, less than; —, not analyzed; nr, not reported]

Sampling date	Event day	Analyzing agency	THMs $CHCl_3$ (µg/L)	THMs $CHCl_2Br$ (µg/L)	THMs $CHClBr_2$ (µg/L)	THMs $CHBr_3$ (µg/L)	Total THMs (µg/L)	Field specific conductance (µS/cm)	Field pH (standard units)	Temperature (°C)	Turbidity (NTU)	Residual free chlorine (mg/L)	Total residual chlorine (mg/L)	Dissolved solids (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Nitrate, as N (mg/L)	Sulfate (mg/L)
04/16/1998	2	AVEK	24.5	5.3	1.2	<0.5	31.0	210	7.0	—	0.07	0.5	0.70	—	8.9	<0.005	—	—
04/22/1998	8	LACDPW	21.8	4.3	.8	<.5	26.9	181	6.3	15	.16	—	1.10	114	6.5	—	1.63	43
04/23/1998	9	AVEK	25.5	4.4	.1	<.5	30.9	190	6.9	—	.11	.5	.70	—	7.0	.01	—	—
04/29/1998	15	LACDPW	17.0	9.9	4.0	<.5	30.9	239	6.82	18	.16	—	.89	150	19.7	—	1.64	64
05/06/1998	22	LACDPW	17.0	15.7	7.3	<.5	40.0	286	6.85	17	nd	—	.76	180	26.1	—	1.59	70
05/07/1998	23	AVEK	17.8	10.6	4.4	<.5	32.8	260	7.2	—	.10	—	—	—	19.4	<.005	—	—
05/13/1998	29	LACDPW	18.2	3.8	<.5	<.5	22.0	150	6.83	13	nd	—	1.16	94	8.7	—	1.08	45
05/14/1998	30	AVEK	19.3	3.7	1.0	<.5	24.0	160	6.7	—	.04	.7	.90	—	7.1	<.005	—	—
05/20/1998	36	LACDPW	20.2	4.2	<.5	<.5	24.4	—	6.67	15	.17	—	—	98	5.8	—	.61	47
05/21/1998	37	AVEK	17.8	2.9	.9	<.5	21.6	160	6.7	—	.19	1.0	1.20	—	6.3	<.005	—	—
05/27/1998	43	LACDPW	18.8	4.1	.7	<.5	23.6	152	6.64	15	.14	—	1.21	94	7	—	1.00	32
05/28/1998	44	AVEK	18.1	3.6	.9	<.5	22.6	160	7.1	—	.09	.8	.95	—	7.2	<.005	—	—
06/03/1998	50	LACDPW	nr	nr	nr	nr	32.8	—	6.53	17	.12	—	—	92	6.8	—	.39	31
06/04/1998	51	AVEK	22.1	2.5	<.5	<.5	24.6	140	6.7	—	.14	.8	.90	—	5.7	<.005	—	—
06/10/1998	57	LACDPW	22.5	6.9	.9	<.5	30.3	154	6.52	18	.13	—	.94	98	8.9	—	.51	35
06/11/1998	58	AVEK	18.0	4.4	<.5	<.5	22.4	180	6.9	—	.09	.5	.70	—	10.1	<.005	—	—
06/16/1998	63	LACDPW	23.1	3.9	.5	<.5	27.5	143	6.48	19	.13	—	1.38	90	6.4	—	.42	33

Table 10. Dissolved organic carbon, residual chlorine, and trihalomethane concentration data, and ultraviolet absorbance data for injection water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Samples analyzed at the U.S. Geological Survey laboratory in Sacramento, California, one day after collection. Event day, number of days since beginning of injection period; DOC, dissolved organic carbon; UVA_{254}, ultraviolet absorbance at 254 nanometers; $SUVA_{254}$, specific ultraviolet absorbance at 254 nanometers; THM, trihalomethane; $CHCl_3$, chloroform; $CHCl_2Br$, bromodichloromethane; $CHClBr_2$, dibromochloromethane; $CHBr_3$, bromoform. $CHBr_3$ less than 0.2 μg/L (microgram per liter) assigned value of 0 μg/L; $CHClBr_2$ less than 0.5 μg/L assigned value of 0.5 μg/L. mg/L, milligram per liter; /cm, per centimeter; (L/mg)/m, liter per milligram per meter; <, less than; —, not analyzed]

Sampling date	Event day	DOC (mg/L)	UVA_{254} (/cm)	$SUVA_{254}$ [(L/mg)/m]	Residual free chlorine (mg/L)	Total residual chlorine (mg/L)	THMs				Total THMs (μg/L)
							$CHCl_3$ (μg/L)	$CHCl_2Br$ (μg/L)	$CHClBr_2$ (μg/L)	$CHBr_3$ (μg/L)	
04/15/1998	1	2.02	0.033	1.6	0.78	0.98	33.9	11.2	2.2	<0.2	47.3
04/16/1998	2	1.94	.032	1.6	.53	.65	32.3	9.6	1.6	<.2	43.5
04/17/1998	3	1.96	.032	1.6	.60	.72	37.1	11.4	1.9	<.2	50.4
04/18/1998	4	1.88	.030	1.6	.83	.92	29.3	8.6	1.2	<.2	39.1
04/19/1998	5	1.96	.030	1.5	.88	1.01	33.4	9.2	1.3	<.2	43.9
04/20/1998	6	1.90	.031	1.6	.96	1.09	32.8	7.4	1.2	<.2	41.4
04/21/1998	7	1.85	.030	1.6	.88	.98	35.2	7.2	1.2	<.2	43.6
04/22/1998	8	1.88	.029	1.5	.75	.86	39.2	7.6	1.2	<.2	48.0
04/23/1998	9	1.86	.029	1.6	.50	.63	36.0	7.6	1.2	<.2	44.8
05/07/1998	23	1.90	.029	1.5	.59	.73	26.0	14.2	5.4	<.2	45.6
05/12/1998	28	1.59	.023	1.5	.82	.94	30.9	8.8	1.0	<.2	40.7
05/13/1998	29	1.56	.022	1.4	.99	1.10	27.3	7.3	.8	<.2	35.4
05/14/1998	30	1.45	.022	1.5	1.01	1.17	26.4	7.6	1.0	<.2	35.0
05/18/1998	34	1.48	.020	1.4	.85	.96	28.7	8.4	1.0	<.2	38.1
05/19/1998	35	1.55	.021	1.4	.88	1.01	21.4	6.0	<1	<.2	27.4
05/20/1998	36	1.54	.022	1.4	1.03	1.14	36.1	7.4	<.5	<.2	43.5
05/21/1998	37	1.56	.020	1.3	—	—	27.9	6.1	<.5	<.2	34.0
05/26/1998	42	2.00	.029	1.5	.72	.85	42.5	10.1	<.5	<.2	52.8
05/27/1998	43	1.80	.024	1.3	.96	1.06	26.5	3.8	<.5	<.2	30.3
05/28/1998	44	1.76	.024	1.4	.98	1.06	30.4	4.1	<.5	<.2	34.5
06/01/1998	48	1.76	.024	1.4	.88	1.00	—	—	—	—	—
06/02/1998	49	1.82	.023	1.3	1.10	1.20	—	—	—	—	—
06/03/1998	50	1.67	.022	1.3	1.33	1.42	—	—	—	—	—
06/04/1998	51	1.71	.022	1.3	.77	.88	28.1	3.8	<.5	<.2	32.1
06/08/1998	55	1.91	.022	1.2	.52	.61	—	—	—	—	—
06/09/1998	56	1.78	.022	1.2	.63	.71	30.9	5.7	<.5	<.2	36.8
06/10/1998	57	1.79	.022	1.2	.75	.82	24.8	5.5	<.5	<.2	30.5
06/11/1998	58	1.78	.022	1.2	.54	.66	30.1	9.6	1.7	<.2	41.4
06/15/1998	62	1.50	.019	1.3	.84	.91	26.3	4.2	<.5	<.2	30.5
06/16/1998	63	1.63	.020	1.2	1.13	1.23	36.1	6.7	<.5	<.2	42.8
06/17/1998	63	1.66	.020	1.2	—	—	—	—	—	—	—

concentrations of dissolved constituents, except the samples collected on April 29, May 6, and May 7, 1998. Specific conductance of the injection water ranged from 140 to 210 µS/cm (microsiemen per centimeter) and the dissolved solids concentrations ranged from 90 to 114 mg/L, except on those three sampling dates when specific conductance ranged from 239 to 286 µS/cm and dissolved solids concentration ranged from 150 to 180 mg/L (fig. 5*A*, table 9). Chloride and sulfate concentrations followed the same pattern as dissolved solids concentrations. They ranged from 5.7 to 10.1 mg/L and from 31 to 47 mg/L, respectively, in most of the injection water samples, but rose to between 19.4 and 26.1 mg/L and between 64 and 70 mg/L, respectively, in the samples collected on April 29, May 6, and May 7, 1998 (fig. 5*B,C*; table 9). Bromide concentrations were generally below the detection limit of the analytical method (less than 0.005 mg/L).

The concentrations of free and total residual chlorine, and the pH, temperature, and turbidity of the injection water did not vary systematically during the injection period. The pH of the injection water varied between 6.3 and 7.2, and the pH values reported by AVEK were systematically higher than those reported by LACDPW (fig. 5*D*, table 9). The reason for this offset is unknown. Total residual chlorine concentrations, which ranged from 0.70 mg/L to 1.38 mg/L, were slightly higher than residual free chlorine concentrations (fig. 5*E*). The temperature of the injection water varied between 13°C and 19°C, and the turbidity was low in nearly all the samples (fig. 5*F*).

Total THM concentrations in the injection water at the time of injection ranged from 22.0 to 40.0 µg/L (fig. 5*G,* table 9) with a mean concentration of 28 µg/L. $CHCl_3$ comprised 80–92 mole percent of the THMs in all the samples, except for the samples collected on April 29, May 6, and May 7, 1998, which were only 52–64 mole percent $CHCl_3$.

The DOC concentration in and the UVA_{254} values of the injection water sample followed a different pattern than that shown by the specific conductance and the dissolved solids concentrations. The DOC concentrations ranged from 1.45 to 2.02 mg/L (fig. 5*H*, table 10) with a mean of 1.76 mg/L and a standard deviation of 0.17 mg/L. Water samples collected between May 12 and May 21, 1998, had lower DOC concentrations than did samples collected during the remaining injection period. The UVA_{254} values ranged from 0.019 to 0.033 /cm (per centimeter), and the samples collected between May 12 and June 17, 1998, had lower UVA_{254} values than the samples collected between April 15 and May 7, 1998 (fig. 5*I,* table 10).

Residual chlorine and THM concentrations measured by the USGS 1 day after sample collection are given in table 10. Total residual chlorine concentrations ranged from 0.61 to 1.42 mg/L (table 10) and were always less than the total residual chlorine concentrations measured in replicate samples by LACDPW or AVEK immediately after sample collection (table 9). Total THM concentrations ranged from 27.4 to 52.8 µg/L 1 day after sample collection; the mean concentration was 39.7 µg/L (table 10). $CHCl_3$ comprised 78–91 mole percent of the THMs in all samples, except the sample collected on May 7, 1998, which had only 66 mole percent $CHCl_3$. Total THM concentrations measured by the USGS 1 day after sample collection (table 10) were always higher than the total THM concentrations measured by LACDPW or AVEK in replicate samples that were quenched at the time of collection (table 9).

Ground Water

Data for the ground-water sample extracted from well 4-32 on March 4, 1998, are shown in figure 5*A–I,* and are given in tables 11, 12, and 13. This sample represents the composition of the ground water in the aquifer near well 4-32 before the injection of imported water during the third cycle. It may not represent the composition of the native ground water in the aquifer because injection water from the two previous cycles may have remained in the aquifer near the well. However, this sample was collected 11 months after the previous injection period had ceased; therefore, it likely contained very little injection water from previous cycles. The ground-water sample had a higher specific conductance, pH, temperature, and dissolved solids concentration than did all of the injection water samples (fig. 5*A,D,F;* tables 9 and 11). The ground-water sample also had a lower DOC concentration and a lower UVA_{254} value than did all of the injection water samples (fig. 5*H, I*; tables 10 and 12). Measured THM concentrations were below detection limits for all four THM species in the ground-water sample analyzed by the USGS, but unfortunately this sample was not collected in headspace-free vials. A concurrent sample collected and analyzed by LACDPW contained 1.7 µg/L $CHCl_3$ (fig. 5*G,* table 13).

Table 11. Water-quality data for extraction water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Samples analyzed at two laboratories: AVEK, Antelope Valley–East Kern Water Agency; LACDPW, Los Angeles County Department of Public Works. Event day, number of days since beginning of extraction period. µS/cm, microsiemen per centimeter; °C, degrees Celsius; NTU, nephelometric turbidity unit; mg/L, milligram per liter; nd, not detected; —, not analyzed; --, ground-water sample]

Sampling date	Event day	Analyzing agency	Field specific conductance (µS/cm)	Field pH (standard units)	Field temperature (°C)	Turbidity (NTU)	Total residual chlorine (mg/L)	Free residual chlorine (mg/L)	Dissolved solids (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Nitrate, as N (mg/L)	Sulfate (mg/L)
03/04/1998	--	LACDPW	313	7.48	21	0.86	nd	—	192	10.9	nd	1.95	23.0
06/30/1998	1	LACDPW	269	6.53	22	.13	1.03	—	192	32.3	nd	.58	47.9
07/01/1998	2	LACDPW	158	6.02	18	8.64	nd	—	110	8.00	nd	.61	36.0
07/01/1998	2	AVEK	160	6.7	—	6.5	.30	0.10	—	7.60	0.007	—	—
07/02/1998	3	LACDPW	164	6.01	18	5.68	nd	—	104	6.87	nd	.46	25.9
07/04/1998	5	LACDPW	169	6.12	18	5.26	nd	—	118	7.20	nd	.56	26.4
07/05/1998	6	LACDPW	174	6.12	18	5.35	nd	—	122	7.47	nd	.59	26.6
07/06/1998	7	LACDPW	178	6.07	18	3.07	nd	—	124	7.38	nd	.64	26.7
07/07/1998	8	LACDPW	183	6.18	18	2.18	nd	—	120	7.99	nd	.66	27.0
07/08/1998	9	LACDPW	190	6.24	18	2.12	nd	—	122	8.25	nd	.76	27.5
07/09/1998	10	LACDPW	192	6.32	18	1.4	nd	—	124	8.54	nd	.73	27.7
07/09/1998	10	AVEK	200	7.1	—	.95	.10	trace	—	9.40	.011	—	—
07/10/1998	11	LACDPW	197	6.38	18	1.12	nd	—	138	8.59	nd	.82	27.4
07/11/1998	12	LACDPW	201	6.32	18	1.13	nd	—	132	8.71	.110	.88	27.5
07/12/1998	13	LACDPW	202	6.27	18	1.14	nd	—	136	8.94	nd	.89	27.6
07/13/1998	14	LACDPW	206	6.35	18	.90	nd	—	138	9.46	nd	.99	30.5
07/14/1998	15	LACDPW	217	6.40	18	1.14	nd	—	134	9.71	nd	.78	30.8
07/16/1998	17	AVEK	220	7.2	—	.40	.20	trace	—	10.7	.012	—	—
07/22/1998	23	LACDPW	237	6.52	19	1.16	nd	—	158	11.3	nd	nd	30.7
07/24/1998	25	AVEK	280	7.5	—	.50	trace	—	—	11.7	.019	—	—
07/27/1998	28	LACDPW	255	6.65	19	1.09	nd	—	160	11.0	nd	1.50	26.4
07/28/1998	29	LACDPW	251	6.61	20	1.08	nd	—	152	11.2	nd	1.49	26.9
07/31/1998	32	AVEK	270	7.5	—	.50	nd	nd	—	12.4	.023	—	—
08/04/1998	36	LACDPW	280	6.80	20	.60	nd	—	178	11.7	nd	1.63	26.6
08/05/1998	37	LACDPW	272	6.81	20	.63	nd	—	172	13.0	nd	2.13	30.4
08/07/1998	39	AVEK	290	7.6	—	.25	.15	nd	—	13.2	.026	—	—
08/12/1998	44	LACDPW	279	6.95	20	.59	nd	—	178	12.1	nd	1.79	25.1
08/14/1998	46	AVEK	290	7.6	—	.55	nd	nd	—	13.9	.027	—	—

Table 11. Water-quality data for extraction water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California—Continued

Sampling date	Event day	Analyzing agency	Field specific conductance (μS/cm)	Field pH (standard units)	Field temperature (°C)	Turbidity (NTU)	Total residual chlorine (mg/L)	Free residual chlorine (mg/L)	Dissolved solids (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Nitrate, as N (mg/L)	Sulfate (mg/L)
08/19/1998	51	LACDPW	292	7.02	20	.48	.04	—	188	13.7	nd	2.09	26.8
08/21/1998	53	AVEK	310	7.9	—	0.15	trace	nd	—	14.5	0.035	—	—
08/26/1998	58	LACDPW	303	7.08	20	.36	0.05	—	194	14.1	nd	2.10	26.0
08/28/1998	60	AVEK	320	7.6	—	.15	trace	trace	—	15.5	.039	—	—
09/03/1998	66	LACDPW	304	7.02	20	.40	.05	—	198	15.4	nd	nd	26.4
09/04/1998	67	AVEK	320	7.9	—	.15	trace	nd		16.0	.041	—	—
09/09/1998	72	LACDPW	308	7.32	20	.43	nd	—	202	15.3	nd	2.21	25.4
09/11/1998	74	AVEK	330	7.9	—	.15	trace	trace	—	16.6	.043	—	—
09/16/1998	79	LACDPW	331	7.54	21	.29	.03	—	210	16.0	nd	—	25.6
09/18/1998	81	AVEK	340	8.1	—	.15	trace	trace	—	16.8	.045	—	—
09/23/1998	86	LACDPW	330	7.48	22	.23	.04	—	206	16.1	nd	2.38	26.0
09/25/1998	88	AVEK	340	8.1	—	.20	nd	nd	—	17.2	.047	—	—
09/30/1998	93	LACDPW	332	7.52	22	.40	nd	—	206	18.1	nd	2.89	29.8
10/02/1998	95	AVEK	340	8	—	.35	trace	trace	—	17.8	.049	—	—
10/07/1998	100	LACDPW	331	7.55	22	.38	nd	—	216	17.5	nd	2.52	26.6
10/09/1998	102	AVEK	350	8.1	—	.20	trace	nd		18.3	.052	—	—
10/14/1998	107	LACDPW	335	7.88	22	.40	nd	—	218	17.3	nd	2.52	26.0
10/16/1998	109	AVEK	360	8.2	—	.25	trace	trace	—	19.1	.051	—	—
10/21/1998	114	LACDPW	347	7.68	22	2.29	nd	—	226	20.0	nd	2.99	27.8
02/10/1999	226	LACDPW	299	6.80	21	3.43	nd	—	186	21.3	nd	4.14	25.2
02/18/1999	234	LACDPW	288	6.87	22	4.75	nd	—	182	15.4	nd	2.43	23.3
02/24/1999	240	LACDPW	290	7.18	22	1.66	nd	—	182	13.9	nd	3.25	22.2
03/03/1999	247	LACDPW	299	7.44	23	.64	nd	—	192	12.2	nd	2.54	10.1
03/10/1999	254	LACDPW	336	7.45	22	4.15	nd	—	210	20.3	nd	4.55	24.4
03/17/1999	261	LACDPW	306	7.37	23	.76	nd	—	184	13.9	.110	3.29	24.5
03/24/1999	268	LACDPW	307	7.43	23	.48	nd	—	184	11.6	.210	2.58	21.1
03/31/1999	275	LACDPW	303	7.41	23	.19	nd	—	192	12.2	nd	2.54	22.1
04/07/1999	282	LACDPW	308	7.29	23	.17	nd	—	214	11.7	nd	2.39	20.5
04/14/1999	289	LACDPW	313	7.25	23	.13	nd	—	192	11.4	nd	2.26	19.9
04/21/1999	296	LACDPW	310	7.27	22	.18	nd	—	206	11.4	nd	2.37	20.2
04/28/1999	303	LACDPW	302	7.35	22	.14	nd	—	212	13.0	nd	2.32	32.0

Table 12. Dissolved organic carbon concentration and ultraviolet absorbance data for extraction water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Samples analyzed at the U.S. Geological Survey laboratory in Sacramento, California. Event day, number of days since beginning of extraction period; DOC, dissolved organic carbon; UVA_{254}, ultraviolet absorbance at 254 nanometers; $SUVA_{254}$, specific ultraviolet absorbance at 254 nanometers. mg/L, milligram per liter; /cm, per centimeter; (L/mg)/m, liter per milligram per meter; --, ground water sample]

Sampling date	Event day	DOC (mg/L)	UVA_{254} (/cm)	$SUVA_{254}$ [(L/mg)/m]
03/04/1998	--	0.2	0.004	2.1
07/22/1998	23	.92	.014	1.5
07/24/1998	25	.92	.014	1.5
07/28/1998	29	.81	.014	1.7
07/31/1998	32	.80	.015	1.9
08/04/1998	36	.78	.016	2.1
08/07/1998	39	.74	.012	1.6
08/11/1998	43	.63	.018	2.8
08/17/1998	49	.58	.013	2.2
08/19/1998	51	.44	.013	3.0
08/26/1998	58	.49	.009	1.8
09/03/1998	66	.44	.009	2.0
09/09/1998	72	.36	.009	2.5
09/16/1998	79	.37	.008	2.2
09/23/1998	86	.37	.008	2.2
09/30/1998	93	.34	.008	2.4
10/07/1998	100	.27	.008	3.0
10/21/1998	114	.31	.007	2.3
02/24/1999	240	.62	.010	1.6
03/10/1999	254	2.43	.008	0.3
03/24/1999	268	1.06	.007	0.7
04/07/1999	282	1.65	.012	0.7

Extraction Water

Data for samples of extraction water collected from well 4-32 are shown in figure 5*A–I*, and are given in tables 11, 12, and 13. The concentrations of dissolved constituents in the extraction water indicated strong, systematic temporal variations during the first phase of the extraction period—June 30, 1998, to October 24, 1998. No pumping occurred at well 4-32 between October 24, 1998, and February 22, 1999 (fig. 3). During this phase of the extraction period, the specific conductance of the extracted water increased from 158 to about 350 µS/cm, and the dissolved solids concentration increased from about 110 to 226 mg/L (fig. 5*A,* table 11). [The concentrations of most dissolved constituents in the sample collected on June 30, 1998, were very different from the concentrations of the constituents in the rest of the extraction water samples (table 11). The reason for these differences is unknown, and that sample has been omitted from the presentation of trends in the data.] The pH, temperature, and the concentrations of chloride, bromide, and nitrate in the extracted water also increased steadily (fig. 5*B, C, D, F*; table 11), whereas the concentration of sulfate decreased slightly (fig. 5*C*; table 11). Total and residual free chlorine concentrations quickly decreased to undetectable levels (fig. 5*E,* table 11). DOC concentrations decreased from 0.92 to 0.31 mg/L and UVA_{254} values from 0.014 to 0.007 /cm between July 22, 1998, and October 24, 1998 (fig. 5*H,I*; table 12). Note that extraction water samples were not collected for analysis of DOC concentration and UVA_{254} value prior to July 22, 1998. Total THM concentrations decreased from 58.9 µg/L on July 1, 1998, to 8.2 µg/L on October 21, 1998, (fig. 5*G,* table 13) and the composition of the THMs decreased from about 90 mole percent $CHCl_3$ to about 75 mole percent $CHCl_3$.

The concentrations of most dissolved constituents varied systematically during the second phase of the extraction period—February 22, 1999, to April 29, 1999—although the patterns of variation were different than those observed during the first phase. The specific conductance of the extracted water generally increased from 290 to 310 µS/cm, and the dissolved solids concentration generally increased from 182 to 212 mg/L (fig. 5*A*, table 11). The concentrations of chloride, sulfate, and nitrate decreased slightly (fig. 5*B,C*; table 11). Total THM concentrations decreased steadily from about 20 to 3 µg/L (fig. 5*G,* table 13), whereas the DOC concentrations varied unsystematically between 0.62 and 2.43 mg/L (fig. 5*H,* table 12).

Water from the Nested Piezometers

Data for samples collected from the nested piezometers during the third cycle are shown in figure 5*G–I,* and are given in table 14. UVA_{254} values measured in samples from the piezometers were considerably more variable than those in samples of extraction water. UVA_{254} values ranged from 0.002 to 0.299 /cm (fig. 5*I,* table 14). Many of the piezometer samples contained very fine grained suspended material that passed through the 0.3-µm pore-size glass fiber filters during filtration. Suspended material increases the apparent light absorbance by water samples because light is scattered off the particles. The presence of this suspended material also may have interfered with the DOC analyses of these samples. DOC concentrations

Table 13. Trihalomethane concentration data for extraction water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Samples analyzed at three laboratories: USGS, U.S. Geological Survey, Sacramento District; AVEK, Antelope Valley–East Kern Water Agency; LACDPW, Los Angeles County Department of Public Works. Event day, number of days since beginning of extraction period; THM, trihalomethane; $CHCl_3$, chloroform; $CHCl_2Br$, bromodichloromethane; $CHClBr_2$; dibromochloromethane; $CHBr_3$, bromoform. µg/L, microgram per liter; nd, not detected; --, ground-water sample]

Sampling date	Event day	Analyzing agency	THMs				Total THMs (µg/L)
			$CHCl_3$ (µg/L)	$CHCl_2Br$ (µg/L)	$CHClBr_2$ (µg/L)	$CHBr_3$ (µg/L)	
03/04/1998	--	LACDPW	1.7	nd	nd	nd	1.7
03/04/1998	--	USGS	nd	nd	nd	nd	nd
06/17/1998		USGS	47.3	8.2	0.2	<0.2	55.7
06/30/1998	1	LACDPW	14.4	14.2	8.2	<.5	36.8
07/01/1998	2	LACDPW	42.6	9.9	1.1	<.5	53.6
07/01/1998	2	AVEK	52.2	6.7	<.5	<.5	58.9
07/02/1998	3	LACDPW	34.5	9.4	<.5	<.5	43.9
07/04/1998	5	LACDPW	28.9	9.6	1.5	<.5	40.0
07/05/1998	6	LACDPW	40.8	11.5	2.0	<.5	54.3
07/06/1998	7	LACDPW	29.0	8.5	1.4	<.5	38.9
07/07/1998	8	LACDPW	28.0	8.4	1.4	<.5	37.8
07/08/1998	9	LACDPW	37.7	12.8	2.2	<.5	52.7
07/09/1998	10	LACDPW	36.2	8.9	1.9	<.5	47.0
07/09/1998	10	AVEK	44.3	6.7	1.5	<.5	52.4
07/10/1998	11	LACDPW	38.2	12.7	2.7	<.5	53.6
07/11/1998	12	LACDPW	29.1	8.5	1.6	<.5	39.2
07/12/1998	13	LACDPW	37.1	11.5	2.5	<.5	51.1
07/13/1998	14	LACDPW	38.1	11.8	2.3	<.5	52.2
07/14/1998	15	LACDPW	34.3	11.1	2.2	<.5	47.6
07/16/1998	17	AVEK	36.3	6.3	1.7	<.5	44.2
07/22/1998	23	USGS	33.5	9.4	1.8	<.2	44.7
07/22/1998	23	LACDPW	24.9	7.9	1.6	<.5	34.4
07/24/1998	25	USGS	17.7	5.0	.8	<.2	23.4
07/24/1998	25	AVEK	27.4	5.0	<.5	<.5	32.4
07/27/1998	28	LACDPW	18.9	6.0	1.7	<.5	26.6
07/28/1998	29	USGS	31.1	8.9	1.6	<.2	41.6
07/28/1998	29	LACDPW	16.8	5.7	1.2	<.5	23.0
07/31/1998	32	USGS	30.7	8.1	1.6	<.2	40.4
07/31/1998	32	AVEK	22.8	4.1	<.5	<.5	26.8
08/04/1998	36	USGS	27.3	8.7	1.7	<.2	37.7
08/04/1998	36	LACDPW	18.4	5.6	1.9	<.5	25.9
08/05/1998	37	LACDPW	22.2	5.1	1.6	<.5	28.9
08/07/1998	39	USGS	25.8	8.0	1.6	<.2	35.4
08/07/1998	39	AVEK	20.4	4.2	1.2	<.5	25.8
08/11/1998	43	USGS	15.2	5.2	1.0	<.2	21.4
08/12/1998	44	LACDPW	22.5	4.3	1.5	<.5	28.3
08/14/1998	46	USGS	25.2	6.3	1.2	<.2	32.7
08/14/1998	46	AVEK	22.8	4.7	1.2	<.5	28.7
08/17/1998	49	USGS	8.3	2.2	.6	<.2	11.0
08/19/1998	51	USGS	20.4	5.6	1.4	<.2	27.4
08/19/1998	51	LACDPW	15.8	3.2	1.1	<.5	20.1
08/21/1998	53	USGS	18.6	5.2	1.2	<.2	25.0

Table 13. Trihalomethane concentration data for extraction water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California—Continued

Sampling date	Event day	Analyzing agency	THMs				Total THMs (μg/L)
			$CHCl_3$ (μg/L)	$CHCl_2Br$ (μg/L)	$CHClBr_2$ (μg/L)	$CHBr_3$ (μg/L)	
08/21/1998	53	AVEK	16.6	3.7	1.2	<0.5	21.5
08/26/1998	58	USGS	19.6	5.7	1.3	<.2	26.6
08/26/1998	58	LACDPW	14.4	3.2	1.3	<.5	18.9
08/28/1998	60	AVEK	13.9	3.5	1.0	<.5	18.5
09/03/1998	66	USGS	14.9	4.6	1.0	<.2	20.5
09/03/1998	66	LACDPW	17.9	4.5	2.7	<.5	25.1
09/04/1998	67	AVEK	13.3	3.2	1.1	<.5	17.6
09/09/1998	72	USGS	13.2	4.4	1.2	<.2	18.8
09/09/1998	72	LACDPW	12.5	2.7	1.1	<.5	16.3
09/11/1998	74	AVEK	10.8	2.8	1.0	<.5	14.6
09/16/1998	79	USGS	12.6	3.8	1.0	<.2	17.3
09/16/1998	79	LACDPW	7.8	2.3	1.0	<.5	11.1
09/18/1998	81	AVEK	9.6	2.6	1.0	<.5	13.2
09/23/1998	86	USGS	12.2	3.9	1.2	<.2	17.2
09/23/1998	86	LACDPW	8.2	2.3	1.0	<.5	11.5
09/25/1998	88	AVEK	8.6	2.5	1.0	<.5	12.0
09/30/1998	93	USGS	10.3	3.9	1.2	<.2	15.4
09/30/1998	93	LACDPW	8.8	2.5	.9	<.5	12.2
10/02/1998	95	AVEK	9.6	2.6	1.0	<.5	13.3
10/07/1998	100	USGS	11.0	3.5	1.2	<.2	15.6
10/07/1998	100	LACDPW	8.0	2.5	.8	<.5	11.3
10/09/1998	102	AVEK	7.5	2.4	1.0	<.5	10.9
10/14/1998	107	LACDPW	7.2	2.6	1.3	<.5	11.1
10/16/1998	109	AVEK	6.4	2.2	1.0	<.5	9.6
10/21/1998	114	USGS	5.9	1.8	.5	<.2	8.2
10/21/1998	114	LACDPW	7.6	3.3	1.2	<.5	12.1
02/10/1999	226	LACDPW	14.1	3.4	1.3	<.5	18.8
02/18/1999	234	LACDPW	20.1	4.8	1.3	<.5	26.2
02/24/1999	240	USGS	11.2	2.8	.6	<.2	14.6
02/24/1999	240	LACDPW	16.8	3.7	1.1	<.5	21.6
03/03/1999	247	LACDPW	9.1	2.4	.9	<.5	12.4
03/10/1999	254	USGS	6.2	1.6	.5	<.2	8.3
03/10/1999	254	LACDPW	5.1	2.0	.6	<.5	7.7
03/17/1999	261	LACDPW	6.9	1.9	.5	<.5	9.3
03/24/1999	268	USGS	6.0	1.5	.5	<.2	8.0
03/24/1999	268	LACDPW	4.6	1.7	.5	<.5	6.8
03/31/1999	275	LACDPW	4.1	1.3	<.5	<.5	5.4
04/07/1999	282	USGS	4.2	1.2	<.5	<.2	5.4
04/07/1999	282	LACDPW	3.7	1.1	<.5	<.5	4.8
04/14/1999	289	LACDPW	2.7	.9	<.5	<.5	3.6
04/21/1999	296	LACDPW	2.3	.8	<.5	<.5	3.1
04/28/1999	303	LACDPW	2.2	.8	<.5	<.5	3.0

ranged from 0.11 to 2.13 mg/L (fig. 5*H*, table 14). Total THM concentrations in water samples from the piezometers ranged from 15.6 to 74.5 μg/L, and were always higher than the total THM concentrations measured in the samples of extraction water collected on the same day (fig. 5*G*, compare tables 14 and 13).

STUDIES OF THE FORMATION AND FATE OF TRIHALOMETHANES

Four studies to investigate the formation and fate of THMs were done during the third injection, storage, and recovery cycle. The first study used laboratory

Table 14. Dissolved organic carbon concentration, ultraviolet absorbance, and trihalomethane concentration data for water collected from nested piezometers 7N/12W-27P6–8 during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Samples analyzed at the U.S. Geological Survey laboratory in Sacramento, California. DOC, dissolved organic carbon; UVA_{254}, ultraviolet absorbance at 254 nanometers; $SUVA_{254}$, specific ultraviolet absorbance at 254 nanometers; THM, trihalomethane; $CHCl_3$, chloroform; $CHCl_2Br$, bromodichloromethane; $CHClBr_2$, dibromochloromethane; $CHBr_3$, bromoform. mg/L, milligram per liter; /cm, per centimeter; (L/mg)/m, liter per milligram per meter; μg/L, microgram per liter; <, less than; —, not analyzed]

Sampling date	DOC (mg/L)	UVA_{254} (/cm)	$SUVA_{254}$ [(L/mg)/m]	THMs				Total THMs (μg/L)
				$CHCl_3$ (μg/L)	$CHCl_2Br$ (μg/L)	$CHClBr_2$ (μg/L)	$CHBr_3$ (μg/L)	
Piezometer 27P6								
02/18/1998[1]	0.17	0.004	2.4	—	—	—	—	—
03/12/1998[1]	.24	.003	1.2	—	—	—	—	—
06/15/1998[1]	1.11	.017	1.5	47.8	8.8	1.0	<0.2	57.6
08/04/1998	1.26	.191	15.1	43.9	11	1.4	<.2	56.3
09/03/1998	1.02	.160	15.7	45.9	8.9	1.2	<.2	56.0
10/07/1998	.91	.061	6.7	58.2	9.9	1.7	<.2	69.8
11/05/1998	1.01	.112	11.0	39.0	6.2	1.0	<.2	46.2
12/02/1998[1]	.82	.105	12.8	33.8	6.1	1.1	<.2	41.0
03/24/1999[1]	1.67	.012	.7	16.0	4.9	1.4	<.2	22.3
Piezometer 27P7								
02/18/1998[1]	0.11	0.003	2.7	—	—	—	—	—
03/12/1998[1]	.18	.003	1.7	—	—	—	—	—
06/15/1998[1]	1.28	.019	1.5	50.2	9.2	0.8	<0.2	60.2
08/04/1998	1.19	.025	2.1	50.5	12.2	1.0	<.2	63.7
09/03/1998	.93	.017	1.8	48.6	9.4	1.0	<.2	59.0
10/07/1998	.86	.017	2.0	62.2	10.7	1.6	<.2	74.5
11/05/1998	.81	.015	1.9	37.0	6.1	.8	<.2	43.9
12/02/1998[1]	.91	—	—	22.2	4.9	.9	<.2	28.0
03/24/1999[1]	.65	.009	1.4	11.2	3.4	1.0	<.2	15.6
Piezometer 27P8								
02/18/1998[1]	0.18	0.002	1.1	—	—	—	—	—
03/12/1998[1]	.46	.006	1.3	—	—	—	—	—
06/15/1998[1]	—	—	—	47.2	8.8	1.0	<0.2	57.0
08/04/1998	1.24	.299	24.2	46.6	13.1	<.5	<.2	59.7
09/03/1998	.60	.021	3.5	26.7	5.8	<.5	<.2	32.5
10/07/1998	.96	.052	5.4	44.1	8.7	<.5	<.2	52.8
11/05/1998	.88	.169	19.2	25.7	6.0	<.5	<.2	31.7
12/02/1998[1]	.73	.033	4.5	23.8	7.2	2.4	<.2	33.4
03/24/1999[1]	2.13	.015	.7	29.8	9.6	.5	<.2	39.9

[1] Sampling took place over 2-day periods; data were combined and listed on first day for convenience.

experiments to examine the formation of THMs from the injection water. The second study evaluated the role of mixing using a conservative tracer, sulfur hexafluoride (SF_6), that was added to the injection water. The third and fourth studies used laboratory experiments to assess the potential for THMs to biodegrade in the aquifer or to sorb to aquifer sediments, respectively.

Formation of Trihalomethanes from Injection Water

Trihalomethanes form by reaction between DOC and free chlorine. The water injected into well 4-32 had been chlorinated at the drinking-water treatment plant and contained approximately 1 mg/L of residual chlorine at the time of injection (table 9). Chlorine continues to react with DOC in the water until either all the chlorine or all the reactive sites in the DOC are consumed. Because THMs are only one of many types of disinfection by-products formed by reaction between chlorine and DOC, no simple relation exists between chlorine consumption and THM formation. In this study, two experiments were completed to determine what factors control the formation of THMs in the aquifer after injection. The storage experiment assessed the capacity of DOC in the injected water to form additional THMs by consuming the residual chlorine present at the time of injection, and the trihalomethane-formation-potential (THMFP) experiment assessed the capacity of the DOC in the injection water to form THMs in the presence of excess chlorine.

Experimental Methods

Storage Experiment Method

The storage experiment consisted of storing unopened vials of injection water for varying periods of time before measuring THM concentrations. The vials were stored in the dark at 25ºC for 1, 2, 4, 8, and 16 weeks. At the end of the storage time, the vials were opened and the concentrations of THMs in the water were measured by the USGS using the method described previously in the “Water-Quality Monitoring at Wells, Analytical Methods” section of this report. Many of the samples could not be analyzed after every storage period because an insufficient number of properly sealed vials were available.

Trihalomethane-Formation-Potential Method

THM-formation potentials (THMFP) for the ground-water and injection-water samples were measured using a modified version of EPA Method 510.1 (U.S. Environmental Protection Agency, 1983). Filtered, purged, and quenched water samples were used for the THMFP tests (see the “Water-Quality Monitoring at Wells, Sampling Methods” section of this report). Samples were adjusted to pH 8.3–8.6 using 0.1 normal sodium hydroxide and then distributed into three 25-mL amber glass serum vials. A boric acid/sodium hydroxide buffer solution of pH 8.3 (1 molar boric acid and 0.11 molar sodium hydroxide) containing 6,000 mg/L of free chlorine was used to dose the samples with 3 mg/L of chlorine per 1 mg/L of DOC, following the reactivity-based dosing method (California Department of Water Resources, 1994; Krasner and Sclimenti, 1994). Chlorinated samples were sealed in the vials headspace-free with aluminum crimp tops and Teflon-faced septa and held for 7 days in the dark at a controlled temperature of 25ºC. At the end of the holding period, one vial was opened, and pH and residual free chlorine concentration were measured. The final pH was 8.3 ± 0.15 and the final residual free chlorine concentration was between 1 and 4 mg/L. The remaining two vials were quenched with 50 μL (microliter) of 0.4-molar sodium sulfite, and the THM concentrations were analyzed by the method described previously in the “Water-Quality Monitoring at Wells, Analytical Methods” section.

Replicate analyses were done on 13 samples to assess analytical precision (table 15). The $\overline{RSD}$ for the 13 pairs of replicate measurements of THMFP was 2.7 percent and the 95-percent confidence interval width was ±1.0 percent, giving an analytical precision of ±3.7 percent.

Results

Storage Experiment

THM concentrations in injection water samples stored for 1, 2, 4, 8, and 16 weeks are shown in figure 6 and given in table 16. Nineteen samples collected during the portion of the injection period between May 7 and June 11, 1998, were analyzed after the 1- and 2-week storage periods. Total THM concentrations in these samples ranged from 36.4 μg/L to 98.2 μg/L, and the average concentration was 74.3 μg/L (fig. 6, table 16). Fifteen samples collected during the portion

Table 15. Quality-assurance and quality-control data for trihalomethane formation potential measurements by the U.S. Geological Survey during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Analytical precision was calculated from results for replicate analyses of 13 samples. Percent relative standard deviation (RSD) was calculated for each sample. The mean RSD ($\overline{RSD}$) and the width of the 95-percent confidence interval about the $\overline{RSD}$ were then calculated. Method analytical precision is the $\overline{RSD}$ plus the absolute value of the confidence interval width. See p. 12 in text for further explanation. Injection samples were collected from well 7N/12W-27P2 (well 4-32). Table is sorted by sampling date. THM, trihalomethane. μg/L, microgram per liter]

Sampling date	Replicate analyses of THMs (μg/L) Run 1	Run 2	Run 3	RSD
04/15/98	164.1	164.2		0.04
04/16/98	153.9	156.4		1.14
04/18/98	138.4	143.7		2.66
04/19/98	135.6	139.9		2.21
04/21/98	132.8	123.9		4.90
04/22/98	135.9	142.7		3.45
04/23/98	147.2	150.4		1.52
05/21/98	113.4	112.3		.69
06/02/98	103.0	97.6		3.81
06/04/98	89.5	83.5		4.90
06/08/98	119.6	112.4		4.39
060/9/98	128.0	139.7	133.9	4.37
06/15/98	107.4	105.6		1.20
Mean relative standard deviation, $\overline{RSD}$, in percent				2.7
95-percent confidence interval width, in percent				±1.0
Method analytical precision, in percent				±3.7

of the injection period between April 15 and May 20, 1998, were analyzed after the 4-week storage period. Total THM concentrations in these samples ranged from 61.3 μg/L to 107.5 μg/L, and the average concentration was 88.8 μg/L (fig. 6, table 16). Twenty-four samples collected during the portion of the injection period between April 15 and May 26, 1998, were analyzed after the 8- and 16-week storage periods. Total THM concentrations in these samples ranged from 68.0 μg/L to 118.9 μg/L, and the average concentration was 94.3 μg/L (fig. 6, table 16). $CHCl_3$ comprised 75 to 88 mole percent of the THMs in samples for all five storage periods except the sample collected on May 7, 1998.

Trihalomethane-Formation-Potential Experiment

Results of the THMFP measurements on the injection-water samples are shown in figure 6 and given in table 17. Table 17 also gives the results for the ground-water sample. The injection-water samples used for the THMFP measurements were purged before chlorination to remove the THMs present in the water at the time that the sample arrived in the USGS laboratory in Sacramento. The THMFP measurement therefore indicates the residual potential of DOC to form additional THMs. The total THMFP is the sum of the THM present in the sample at the time of arrival at the USGS laboratory in Sacramento (table 10) and the residual THMFP. Total THMFP for the injection water samples ranged from 118.8 μg/L to 227.6 μg/L and averaged 175.1 μg/L (fig. 6, table 17). $CHCl_3$ comprised 87 to 95 molar percent of the THMs representing the total THMFP of the injection water samples. The only exception was the sample collected on May 7, 1998, which had only 84 percent $CHCl_3$. Total THMFP of the ground-water sample was 21.1 μg/L (table 17) and the THMs were composed of 21 molar percent $CHCl_3$, 34 molar percent each of $CHCl_2Br$ and $CHClBr_2$, and 11 molar percent of $CHBr_3$.

The THMFP measurements also provide information about the compositional nature of the DOC. Specific trihalomethane formation potential (STHMFP) is defined as the amount of THM formed normalized to the amount of organic carbon present in the original sample. STHMFP is expressed in units of millimoles of THM per mole of DOC (mmol/mol). Total STHMFP values for the injection water samples ranged from 6.9 to 11.3 mmol/mol (table 17), and averaged 9.7 mmol/mol. The STHMFP value for the ground-water sample was 7.3 mmol/mol.

Tracing the Injection Water with Sulfur Hexafluoride

One process that may have affected the THM concentrations during the extraction period was mixing between the injected water and ground water. The mixing hypothesis was evaluated experimentally by doing a tracer study. In this study, a tracer compound not present in the ground water was added to the injected water and then the concentration of the tracer was measured in the extraction water and the samples from the nested piezometers. The tracer compound was unreactive with residual chlorine, not biodegradable, and not likely to adsorb to aquifer sediment; thus, it would not be affected by any of the other processes potentially occurring in the aquifer. Therefore, the tracer provided a means of directly measuring the relative amount of injected water and ground water in a given sample of extracted water.

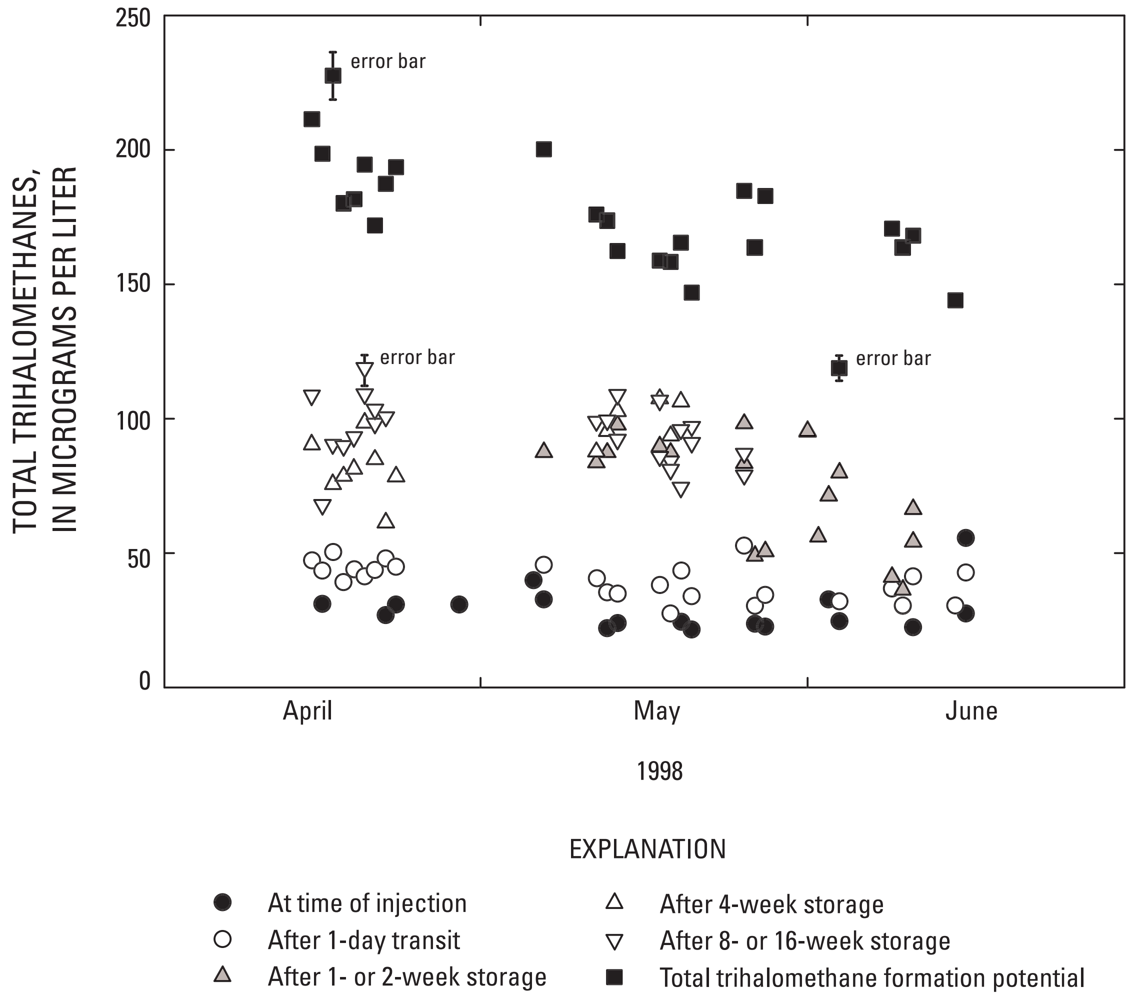

Figure 6. Total trihalomethane concentrations in injection water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California. Trihalomethane (THM) concentrations were measured in injection water sampled at the time of injection into the well, after a 1-day transit of the samples to the U.S. Geological Survey laboratory, and after storage periods of 1, 2, 4, 8, and 16 weeks. Concentrations were also measured after the trihalomethane formation potential (THMFP) experiments. The analytical precisions determined in this report for THMFP and the total THM concentrations are applied to the data. Analytical precision for the THMFP data is shown by error bars on the data points representing the largest and smallest measured THMFPs; error bars for the other data points are not shown but their magnitudes are in between those of the two error bars shown. Analytical precision for the total THM concentration data is shown by the error bar on the data point representing the highest concentration; error bars are not shown with the other data points. The size of the error bar decreases as concentration decreases until it is smaller than the size of the symbols for concentrations less than 61 micrograms per liter.

Experimental Methods

Sulfur hexafluoride (SF_6) was used as a tracer compound in this project. SF_6 is an inert, synthetic compound, normally not present in surface water or ground water in measurable quantities, and it is detectable at low concentrations (Clark and others, 1996). SF_6 was added to the injection water stream about 65 ft from the wellhead through a fritted inlet inserted into the center of the 24-inch-diameter water-supply line. The SF_6 was provided as a calibrated gas mixture of 100 parts per million of SF_6 in nitrogen. Gas-flow rate was controlled at 70 mL/min (milliliter per minute) by a two-stage, high-purity regulator and a micrometering valve. The target solution concentration in the injection waters was 100 pmol/L (picomole per liter). Gas-flow rates measured with a calibrated rotometer showed a variation between 50 and 90 mL/min, presumably because of variations in the overpressure exerted by the water stream at different water-flow velocities. The wellhead sampling port was about 50 ft (more than 10 pipe diameters) from the gas

Table 16. Trihalomethane concentration data for storage experiments on injection water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Samples analyzed at the U.S. Geological Survey laboratory in Sacramento, California. Samples were analyzed after storage for 1, 2, 4, 8, and 16 weeks after collection. $CHCl_3$, chloroform; $CHCl_2Br$, bromodichloromethane; $CHClBr_2$, dibromochloromethane; $CHBr_3$, bromoform; THM, trihalomethane. µg/L, microgram per liter; ns, not sampled; —, not analyzed; <, less than]

Sampling date	Event day	1 week					2 weeks					4 weeks				
		THMs				Total	THMs				Total	THMs				Total
		$CHCl_3$ (µg/L)	$CHCl_2Br$ (µg/L)	$CHClBr_2$ (µg/L)	$CHBr_3$ (µg/L)	THMs (µg/L)	$CHCl_3$ (µg/L)	$CHCl_2Br$ (µg/L)	$CHClBr_2$ (µg/L)	$CHBr_3$ (µg/L)	THMs (µg/L)	$CHCl_3$ (µg/L)	$CHCl_2Br$ (µg/L)	$CHClBr_2$ (µg/L)	$CHBr_3$ (µg/L)	THMs (µg/L)
04/15/1998	1	ns	ns	ns	ns	ns	—	—	—	—	—	67.9	19.0	3.6	<1	90.5
04/16/1998	2	ns	ns	ns	ns	ns	—	—	—	—	—	—	—	—	—	—
04/17/1998	3	ns	ns	ns	ns	ns	—	—	—	—	—	57.5	15.5	2.6	<.2	75.6
04/18/1998	4	ns	ns	ns	ns	ns	—	—	—	—	—	62.1	14.3	2.2	<.2	78.6
04/19/1998	5	ns	ns	ns	ns	ns	—	—	—	—	—	65.5	14.2	1.7	<.2	81.4
04/20/1998	6	ns	ns	ns	ns	ns	—	—	—	—	—	79.8	16.8	1.9	<.2	98.5
04/21/1998	7	ns	ns	ns	ns	ns	—	—	—	—	—	68.2	14.9	1.7	<.2	84.8
04/22/1998	8	ns	ns	ns	ns	ns	—	—	—	—	—	49.5	10.7	1.1	<.2	61.3
04/23/1998	9	ns	ns	ns	ns	ns	—	—	—	—	—	63.9	13.7	.8	<.2	78.5
05/07/1998	23	ns	ns	ns	ns	ns	53.0	24.2	10.1	0.3	87.6	—	—	—	—	—
05/12/1998	28	ns	ns	ns	ns	ns	68.1	14.8	.8	<.2	83.7	75.0	11.8	.9	<.2	87.7
05/13/1998	29	ns	ns	ns	ns	ns	72.7	14.2	.6	<.2	87.5	82.4	12.1	.9	<.2	95.4
05/14/1998	30	ns	ns	ns	ns	ns	84.7	13.0	<.5	<.2	97.7	87.8	13.6	1.4	<.2	102.8
05/18/1998	34	ns	ns	ns	ns	ns	77.3	12.4	<2	<.2	89.7	91.9	14.3	1.3	<.2	107.5
05/19/1998	35	ns	ns	ns	ns	ns	75.5	10.9	1.1	<.2	87.5	81.1	11.6	.9	<.2	93.6
05/20/1998	36	ns	ns	ns	ns	ns	—	—	—	—	—	93.4	12.2	.7	<.2	106.3
05/21/1998	37	ns	ns	ns	ns	ns	—	—	—	—	—	—	—	—	—	—
05/26/1998	42	70.9	11.4	1.1	<0.2	83.4	84.8	12.4	1.0	<.2	98.2	—	—	—	—	—
05/27/1998	43	ns	ns	ns	ns	ns	43.1	5.9	<.5	<.2	49.0	ns	ns	ns	ns	ns
05/28/1998	44	ns	ns	ns	ns	ns	44.5	6.2	<.5	<.2	50.7	ns	ns	ns	ns	ns
06/01/1998	48	79.9	13.9	1.4	<.2	95.2	80.6	13.6	1.3	<.2	95.5	ns	ns	ns	ns	ns
06/02/1998	49	ns	ns	ns	ns	ns	49.8	6.3	<.5	<.2	56.1	ns	ns	ns	ns	ns
06/03/1998	50	ns	ns	ns	ns	ns	64.6	6.7	<.5	<.2	71.3	ns	ns	ns	ns	ns
06/04/1998	51	71.4	8.6	<.5	<.2	80.0	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/08/1998	55	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/09/1998	56	ns	ns	ns	ns	ns	36.0	5.1	<.5	<.2	41.1	ns	ns	ns	ns	ns
06/10/1998	57	ns	ns	ns	ns	ns	31.4	5.0	<.5	<.2	36.4	ns	ns	ns	ns	ns
06/11/1998	58	42.4	10.4	1.4	<.2	54.2	52.0	12.4	1.9	<.2	66.3	ns	ns	ns	ns	ns
06/15/1998	62	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/16/1998	63	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Table 16. Trihalomethane concentration data for storage experiments on injection water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California—Continued

Sampling date	Event day	8 weeks					16 weeks				
		THMs				Total THMs (μg/L)	THMs				Total THMs (μg/L)
		$CHCl_3$ (μg/L)	$CHCl_2Br$ (μg/L)	$CHClBr_2$ (μg/L)	$CHBr_3$ (μg/L)		$CHCl_3$ (μg/L)	$CHCl_2Br$ (μg/L)	$CHClBr_2$ (μg/L)	$CHBr_3$ (μg/L)	
04/15/1998	1	88.6	17.3	2.7	<0.2	108.7	ns	ns	ns	ns	ns
04/16/1998	2	55.9	10.9	1.2	<.2	68.0	ns	ns	ns	ns	ns
04/17/1998	3	74.4	14.3	1.8	<.2	90.5	ns	ns	ns	ns	ns
04/18/1998	4	75.3	13.2	1.3	<.2	89.8	ns	ns	ns	ns	ns
04/19/1998	5	79.5	12.6	1.1	<.2	93.2	ns	ns	ns	ns	ns
04/20/1998	6	102.2	15.3	1.4	<.2	118.9	89.4	17.9	1.8	<0.2	109.1
04/21/1998	7	84.2	13.0	1.0	<.2	98.2	83.9	17.7	1.8	<.2	103.4
04/22/1998	8	85.7	13.6	1.3	<.2	100.6	ns	ns	ns	ns	ns
04/23/1998	9	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
05/07/1998	23	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
05/12/1998	28	76.5	20.1	2.4	<.2	99.1	ns	ns	ns	ns	ns
05/13/1998	29	78.8	18.7	1.8	<.2	99.3	ns	ns	ns	ns	ns
05/14/1998	30	85.7	20.9	2.3	<.2	108.9	78.2	12.4	1.6	<.2	92.2
05/18/1998	34	84.2	20.5	2.1	<.2	106.8	72.4	12.0	1.5	<.2	85.9
05/19/1998	35	74.7	9.5	<.5	<.2	84.2	69.4	10.5	1.1	<.2	81.0
05/20/1998	36	66.8	7.5	<.5	<.2	74.3	83.5	11.4	1.0	<.2	95.9
05/21/1998	37	85.6	11.4	<.5	<.2	97.1	78.7	11.2	1.1	<.2	91.0
05/26/1998	42	75.7	11.2	<.5	<.2	87.1	66.1	11.4	1.5	<.2	79.0
05/27/1998	43	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
05/28/1998	44	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/01/1998	48	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/02/1998	49	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/03/1998	50	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/04/1998	51	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/08/1998	55	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/09/1998	56	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/10/1998	57	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/11/1998	58	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/15/1998	62	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
06/16/1998	63	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Table 17. Trihalomethane formation potential data for injection water and for ground water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Samples analyzed at the U.S. Geological Survey laboratory, Sacramento, California. Event day, number of days since the beginning of the injection period. $CHCl_3$, chloroform; $CHCl_2Br$, bromodichloromethane; $CHClBr_2$, dibromochloromethane; $CHBr_3$, bromoform. Residual THMFP (trihalomethane formation potential) is the sum of $CHCl_3$, $CHCl_2Br$, $CHClBr_2$, and $CHBr_3$ and was measured on sparged, quenched samples. STHMFP, specific trihalomethane formation potential (millimoles of trihalomethane formed per mole of dissolved organic carbon); Cl_2 consumed, chlorine consumed during 7 days of reaction with the sample; total THMFP, sum of residual THMFP and THM concentrations before sparging (table 10). µg/L, microgram per liter; mmol/mol, millimole per mole; mg/L, milligram per liter; —, not analyzed; <, less than; nd, not determined because THM concentrations before sparging were not measured; --, ground-water sample]

Sampling date	Event day	THMs $CHCl_3$ (µg/L)	$CHCl_2Br$ (µg/L)	$CHClBr_2$ (µg/L)	$CHBr_3$ (µg/L)	Residual THMFP (µg/L)	Residual STHMFP (mmol/mol)	Cl_2 consumed (mg/L)	Total THMFP (µg/L)	Total STHMFP (mmol/mol)
03/06/1998	--	2.9	6.5	8.3	3.4	21.1	7.3	—	21.1	7.3
04/15/1998	1	145.6	16.7	1.8	<1	164.1	7.9	4.0	211.4	10.1
04/16/1998	2	138.0	15.6	1.5	<.2	155.1	7.8	3.6	198.6	9.9
04/17/1998	3	164.2	11.7	1.3	<.2	177.2	8.9	5.9	227.6	11.3
04/18/1998	4	131.4	9.6	<1	<.2	141.0	7.4	3.3	180.1	9.3
04/19/1998	5	129.0	8.8	<.2	<.2	137.8	6.9	3.6	181.7	9.0
04/20/1998	6	145.3	7.3	.5	<.2	153.1	8.0	5.2	194.5	10.0
04/21/1998	7	120.6	7.8	<.2	<.2	128.4	6.9	2.6	172.0	9.1
04/22/1998	8	131.1	8.2	<.2	<.2	139.3	7.4	3.9	187.3	9.8
04/23/1998	9	138.2	9.8	.8	<.2	148.8	7.9	3.7	193.6	10.2
05/07/1998	23	131.2	19.4	4.0	<.2	154.6	7.8	2.5	200.2	9.9
05/12/1998	28	124.8	9.9	.6	<.2	135.3	8.4	2.6	176.0	10.8
05/13/1998	29	128.4	9.3	.6	<.2	138.3	8.7	4.1	173.7	10.9
05/14/1998	30	118.2	8.7	.6	<.2	127.5	8.6	3.1	162.5	10.9
05/18/1998	34	111.2	8.8	.8	<.2	120.8	8.0	3.2	158.9	10.4
05/19/1998	35	121.8	8.3	.8	<.2	130.9	8.3	3.3	158.3	10.0
05/20/1998	36	113.6	7.7	.6	<.2	121.9	7.8	4.0	165.4	10.5
05/21/1998	37	106.1	6.3	.4	<.2	112.8	7.2	3.7	146.8	9.2
05/26/1998	42	121.8	9.5	.7	<.2	132.0	6.5	6.4	184.8	9.0
05/27/1998	43	123.7	9.1	.6	<.2	133.4	7.3	4.0	163.7	8.9
05/28/1998	44	133.6	13.6	1.1	<.2	148.3	8.2	3.5	182.8	10.1
06/01/1998	48	145.7	11.7	1.1	<.2	158.5	8.9	3.7	nd	nd
06/02/1998	49	95.7	4.4	.2	<.2	100.3	5.5	4.4	nd	nd
06/03/1998	50	135.2	7.7	.5	<.2	143.4	8.5	3.9	nd	nd
06/04/1998	51	82.3	4.2	.2	<.2	86.7	5.0	3.9	118.8	6.9
06/08/1998	55	107.4	8.2	.4	<.2	116.0	6.0	6.7	nd	nd
06/09/1998	56	123.6	9.8	.5	<.2	133.9	7.4	4.5	170.7	9.4
06/10/1998	57	119.1	13.0	1.1	<.2	133.2	7.3	4.1	163.7	8.9
06/11/1998	58	109.8	15.1	1.8	<.2	126.7	6.9	5.7	168.1	9.0
06/15/1998	62	106.5	6.8	.2	<.2	113.5	7.5	3.3	144.0	9.5

injection site; therefore, the SF_6 theoretically was well mixed into the water stream at the sampling port.

Samples for SF_6 analysis were collected at the sampling port on well 4-32 during both the injection and the extraction periods of the cycle. The sampling port was flushed for several minutes before sample collection to ensure removal of any gas buildup inside the lines. The 30-mL samples were collected in 100-mL gas-tight syringes fitted with sample lock valves in their tips. The tip of each syringe was coupled directly to the sampling port with Teflon tubing and a gate-port valve. Samples also were collected from the nested piezometers. All samples were collected in duplicate. The syringes were shipped on ice overnight to the USGS Sacramento laboratory for processing.

SF_6 was extracted from the water samples by adding 20 mL of ultra-high-purity nitrogen gas to the sample through the nose of the syringe and then shaking the syringe vigorously for 5 minutes. The SF_6 was effectively purged into the nitrogen by this process. The gas was then transferred to a 20-mL vacutainer to await analysis.

The gas samples were shipped to the University of California, Santa Barbara, for analysis. SF_6 concentrations were measured on a gas chromatograph fitted with an electron-capture detector (Wannikhof and others, 1987; Clark and others, 1994). Detector response was calibrated approximately every 30 minutes by analyzing two Scott-Marrin certified standards that contained 6.6 and 88 pmol/L of SF_6. The minimum detection limit of the method was 0.04 pmol/L, and the instrument precision was ±3 percent.

Results

SF_6 concentrations in samples collected from well 4-32 during the injection and extraction periods and from the nested piezometers are shown in figure 7 and given in tables 18, 19, and 20, respectively. There was poor agreement between the SF_6 concentrations measured in replicate samples. In this study, agreement between replicate samples ranged from 0 to 135 percent, whereas in other studies, replicate samples

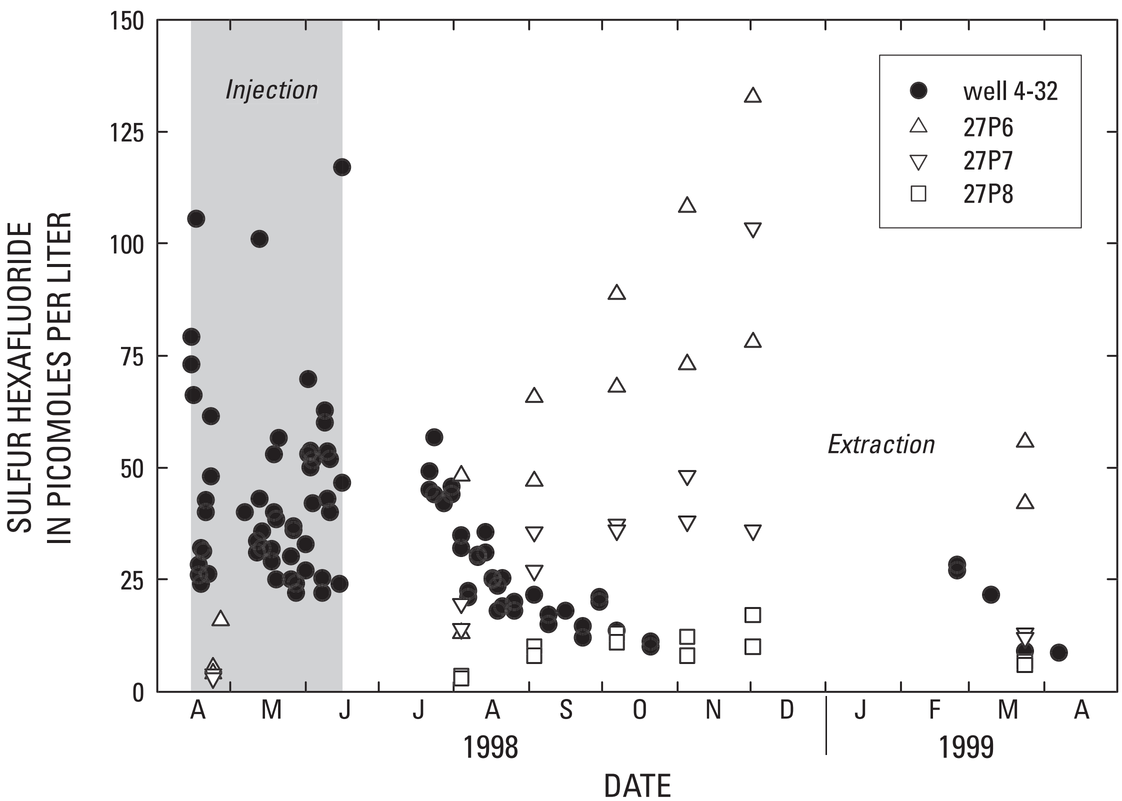

Figure 7. Sulfur hexafluoride concentrations in injection and extraction water collected from well 7N/12W-27P2 (well 4-32) and in water collected from nested piezometers 7N/12W-27P6–8 during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California.

Table 18. Sulfur hexafluoride concentrations in injection water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Samples analyzed at the University of California, Santa Barbara, laboratory. Event day, number of days since beginning of injection period; SF_6, sulfur hexafluoride. pmol/L, picomole per liter; —, not analyzed]

Sampling date	Event day	Replicate analyses of SF_6 (pmol/L)	
		Run 1	Run 2
04/15/1998	1	79	73
04/16/1998	2	66	—
04/17/1998	3	105	—
04/18/1998	4	28	26
04/19/1998	5	32	24
04/20/1998	6	31	—
04/21/1998	7	43	40
04/22/1998	8	26	—
04/23/1998	9	61	48
05/07/1998	23	40	—
05/12/1998	28	34	31
05/13/1998	29	101	43
05/14/1998	30	36	32
05/18/1998	34	32	29
05/19/1998	35	53	40
05/20/1998	36	38	25
05/21/1998	37	57	—
05/26/1998	42	30	25
05/27/1998	43	37	36
05/28/1998	44	24	22
06/01/1998	48	33	27
06/02/1998	49	70	53
06/03/1998	50	54	50
06/04/1998	51	52	42
06/08/1998	55	25	22
06/09/1998	56	63	60
06/10/1998	57	54	43
06/11/1998	58	52	40
06/15/1998	62	24	—
06/16/1998	63	47	—

Table 19. Sulfur hexafluoride concentrations in extraction water collected from well 7N/12W-27P2 (well 4-32) during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Samples analyzed at the University of California, Santa Barbara, laboratory. Event day, number of days since beginning of extraction period; SF_6, sulfur hexafluoride. pmol/L, picomole per liter; —, not analyzed]

Sampling date	Event day	Replicate analyses of SF_6 (pmol/L)	
		Run 1	Run 2
07/22/1998	23	49	45
07/24/1998	25	57	44
07/28/1998	29	42	42
07/31/1998	32	46	44
08/04/1998	36	35	32
08/07/1998	39	22	21
08/11/1998	43	30	30
08/14/1998	46	35	31
08/17/1998	49	25	25
08/19/1998	51	24	18
08/21/1998	53	25	19
08/26/1998	58	20	18
09/03/1998	66	22	—
09/09/1998	72	17	15
09/16/1998	79	18	18
09/23/1998	86	15	12
09/30/1998	93	21	20
10/07/1998	100	14	—
10/21/1998	114	11	10
02/24/1999	240	28	27
03/10/1999	254	22	—
03/24/1999	268	9	—
04/07/1999	282	9	—

agree to within 3 percent (for example, Clark and others, 1996). The two probable causes for the poor agreement between replicate samples were an error in the sample collection procedure and an inadequate method for adding SF_6 to the injection water stream. The field methods used to collect the SF_6 samples and to add SF_6 to the water stream had been newly developed for this project.

An error in the field collection procedure probably caused poor agreement between replicate samples of injection and extraction water, and water from the nested piezometers. The sampling protocol required that the 30-mL samples of water be collected with no air bubbles in the syringes. Thus, any air bubbles trapped in the syringe during sample collection were ejected from the syringe. Unfortunately, SF_6 apparently had begun to equilibrate between the water

Table 20. Sulfur hexafluoride concentrations in water collected from nested piezometers 7N/12W-27P6–8 during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Samples analyzed at the University of California, Santa Barbara, laboratory. SF_6, sulfur hexafluoride. pmol/L, picomole per liter; —, not analyzed]

Sampling date	Replicate analyses of SF_6 (pmol/L)					
	27P6		27P7		27P8	
	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
04/24/1998	5	4	4	3	—	—
04/27/1998	16	—	—	—	—	—
08/04/1998	48	13	20	14	3	3
09/03/1998	66	47	36	27	10	8
10/07/1998	89	68	37	36	13	11
11/05/1998	108	73	48	38	12	8
12/02/1998	133	78	103	36	17	10
03/24/1999	56	42	13	12	7	6

and the air bubbles; therefore, removing the air bubbles reduced the SF_6 concentration in the water. Because no records were kept of air bubble ejection, it was impossible to know which samples yielded SF_6 concentrations that were too low because of this sample-collection error. On the basis of this experience, the sampling protocol for future cycles was revised to allow air bubbles in the syringes.

An inadequate method for adding SF_6 to the injection water stream likely caused poor agreement between samples of injection water. The variability of measured SF_6 concentrations in the injection water was large (fig. 7), even though the rate of adding SF_6 to the water stream was relatively constant. Although the distance between the gas introduction port and the sampling port was theoretically long enough to ensure complete mixing between the added gas bubbles and the water stream, complete mixing apparently did not occur. However, mixing probably was complete by the time the water flowed into the aquifer. The SF_6 should have been added to the injection water stream by way of a gas-water equilibration chamber so that SF_6-saturated water would have been the component added to the water stream. Based on this experience, a gas-water equilibration chamber was designed for use in future cycles.

The variability in SF_6 concentrations between replicate samples of extraction water and of samples from the nested piezometers was less than that between replicate samples of injection water because these samples were only affected by the error in the field collection procedure. The mean RSD for the 38 pairs of replicate samples was 16 percent.

Measured SF_6 concentrations in the injection water ranged from 22 pmol/L to 105 pmol/L (fig. 7, table 18), and the average concentration was 43 pmol/L (RSD = 43 percent). SF_6 concentrations in the extraction water decreased systematically from about 57 pmol/L on July 22, 1998, to 9 pmol/L on April 7, 1999 (fig. 7, table 19). SF_6 concentrations in water from piezometers 27P6 and 27P7 varied widely, ranging from 4 pmol/L to 133 pmol/L and from 3 pmol/L to 103 pmol/L, respectively; whereas, SF_6 concentrations in water from piezometer 27P8 only ranged from 3 pmol/L to 17 pmol/L (fig. 7, table 20).

Biodegradation of Trihalomethanes by Aquifer Bacteria

Another process that may have affected THM concentrations during the extraction period was biodegradation of THMs by bacteria present in the aquifer. The biodegradation hypothesis was evaluated by doing two types of laboratory experiments: sediment microcosm and water enrichment experiments. The sediment microcosms consisted of aquifer sediment and ground water, and the water enrichments consisted of ground water or extraction water amended with the bacteria and particles concentrated from a larger volume of water. Live and sterilized vials of sediment microcosms and water enrichments were prepared. $CHCl_3$ and $CHBr_3$ were added to the vials and the amounts were monitored during an incubation period. Biodegradation of the $CHCl_3$ or $CHBr_3$ by bacteria present in the aquifer sediment or in the water samples would be indicated in these experiments by a decrease in amount of $CHCl_3$ or $CHBr_3$ detected in the live vial relative to the amount detected in the corresponding sterile vial.

A further concern was whether injection, storage, and recovery cycles affect the population of bacteria in the aquifer. A pilot study was done to determine whether bacterial population densities were affected. Bacterial densities were measured in water samples collected from wells and the nested piezometers. The types of bacteria present in the samples were not identified.

Experimental Methods

Sediment Microcosm Method

Sediment microcosms were constructed using sediment from the core taken from the depth corresponding to that of the screened interval of piezometer 27P7 (fig. 2, table 2). The sediment was collected aseptically from the center portion of the core and care was taken to collect a sample free of driller's mud and particles of plastic.

Sediment microcosm incubations were started by placing 20 grams of sediment and 10 mL of ground water (collected from well 4-32 on March 4, 1998) into 100-mL serum vials stoppered with Teflon-lined silicone septa. Enriched sediment microcosms were made by amending sediment microcosms with potassium dihydrogen phosphate (KH_2PO_4) (0.02 gram per liter), ammonium chloride (NH_4Cl) (0.5 gram per liter), and vitamins including B_{12} (1 milliliter per liter) (Pfennig, 1978). The microcosms were spiked with $CHCl_3$ or $CHBr_3$ and then incubated for 145 days under aerobic or anaerobic conditions. Anaerobic conditions were established by flushing the headspace of the vial with nitrogen to remove all oxygen. Sterile controls were prepared by autoclaving some of the vials containing sediment microcosms or enriched sediment microcosms. The mass of $CHCl_3$ or $CHBr_3$ in each vial was measured several times during the incubation period.

Water Enrichment Method

Ground water and extraction water were used to construct the water enrichment incubations. Ground water was collected on March 6, 1998, and extraction water was collected on August 14, 1998, from well 4-32. Both water samples were stored at 4°C until the incubations were established in September 1998. The incubations consisted of water amended with KH_2PO_4, NH_4Cl, and vitamins, plus the bacteria and particles concentrated from a larger volume of water. No sediment was added to these incubations.

Bacteria and particles in the extraction water were concentrated by centrifugation or filtration. One liter of water was centrifuged at 14,000 revolutions per minute. No visible pellet was formed. The upper portion of the water was decanted and the lower portion (120 mL total) was poured into three separate serum vials (30 mL of water into each 100-mL vial). To concentrate bacteria and particles by filtration, two liters of extraction water was passed through a 0.2-μm pore size filter. Bacteria and particles trapped on the filter were resuspended by placing the entire filter into a serum vial containing 30 mL of extraction water. The same procedure was used for the ground water. All of the vials were stoppered with Teflon-lined silicone septa, spiked with $CHCl_3$ and $CHBr_3$, and then incubated for 83 days under aerobic conditions. The mass of $CHCl_3$ and $CHBr_3$ in each vial was measured several times during the incubation period.

Sterile controls consisted of autoclaved extraction water amended with KH_2PO_4, NH_4Cl, and vitamins. Because these controls did not contain filters, a separate control experiment was done to investigate whether THMs were adsorbed onto the filter paper. Extraction water was collected on July 22, 1999, filtered through a 0.2-μm pore size filter, autoclaved, and then poured into six sterile serum vials (30 mL of water into each 100-mL vial). Sterile filters were added to three of the vials. All of the vials were stoppered with Teflon-lined silicone septa, spiked with $CHCl_3$ and $CHBr_3$, and then incubated for 29 days under aerobic conditions. The mass of $CHCl_3$ and $CHBr_3$ in each vial was measured several times during the incubation period.

Trihalomethane Addition and Analysis Methods

All of the vials in the sediment microcosm and water enrichment experiments were spiked with solutions containing known concentrations of $CHCl_3$ and $CHBr_3$. The solutions were prepared by mixing 1 μL of neat $CHCl_3$ or $CHBr_3$ (99 percent, Chem Service) into 10 mL of filtered ground water and were injected into the vials using a microliter syringe to achieve the desired concentrations. Sediment microcosm and anaerobic enriched sediment microcosms received 1.1 μg (microgram) $CHCl_3$ per vial (approximately 106 μg/L in the water) or 1.5 μg $CHBr_3$ per vial (approximately 145 μg/L in the water). Aerobic enriched sediment microcosms received 6.1 μg $CHCl_3$ per vial (approximately 608 μg/L in the water) or 13 μg $CHBr_3$ per vial (approximately 1,279 μg/L in the water). Water enrichment incubations and control experiments with filters received both $CHCl_3$ (5.8 μg per vial; approximately 195 μg/L in the water) and $CHBr_3$ (11.4 μg per vial; approximately 380 μg/L in the water) into the same serum vials. The concentrations in the water are only approximate concentrations because matrix effects and partitioning into vial headspace were not taken into account; therefore, results are presented in terms of μg of $CHCl_3$ or $CHBr_3$ per vial.

The mass of $CHCl_3$ and (or) $CHBr_3$ in each vial was measured by headspace gas chromatography. Gas (200 μL) from the headspace in the vials was extracted by syringe and injected into a gas chromatograph equipped with an electron-capture detector. A Hewlett-

Packard 5890 Series II gas chromatograph equipped with a 4-ft × 1/8-in. Carbopack B column (Supelco) was used. The oven temperature was kept at 200°C for all analyses except for $CHCl_3$ from the enriched sediment microcosm samples, which were run at 160°C. Analysis of $CHCl_3$ and $CHBr_3$ from the filter control experiments was done on a Hewlett-Packard 5890 Series II gas chromatograph equipped with a 30-m Restek RTX-624 wide-bore capillary column employing a temperature ramp (50°C for 0 min; 20°C/min to 160°C for 1 min). The injector temperature was 240°C and the detector was 325°C. Headspace injections of 100 μL were used with this system. Two to four aliquots of headspace gas were analyzed from each vial, and the results were averaged to yield the reported $CHCl_3$ and $CHBr_3$ data. Concentrations were quantified using standard curves that were constructed by analyzing headspace gas from vials prepared with water containing known amounts of $CHCl_3$ and $CHBr_3$. Autoclaved sediment-water mixtures or autoclaved ground water or extraction water was used to prepare $CHCl_3$ and $CHBr_3$ standards to compensate for potential matrix effects. The same set of standard vials was used to construct a new standard curve on each day of the incubation period that vials from the same experiment were analyzed to compensate for nonbiological losses of $CHCl_3$ and $CHBr_3$. Although silicone was applied to the septa after extraction of the headspace gas sample from each vial, the numerous punctures likely compromised the Teflon linings of the septa, allowing some leakage of $CHCl_3$ and $CHBr_3$. For example, the loss of $CHCl_3$ after 20 days from the standard vials associated with the sediment microcosm samples was not systematic—some standard vials showed a 7-percent decrease in response on the gas chromatograph, whereas others showed a 12-percent increase. However, after 80 days all the standard vials showed a 34-percent decrease in response on the gas chromatograph. Losses of $CHBr_3$ were more pronounced; after 80 days, the standard vials showed a 56-percent decrease in response on the gas chromatograph.

Bacterial Counting Method

Water samples were collected from wells 4-32, 4-13, 4-33, and 4-42 and from the nested piezometers to monitor bacterial cell densities. Water samples were collected in sterile, 2.0-mL cryotubes. Glutaraldehyde (4 percent) was added to samples to preserve the cells, and samples were stored at –70°C until the cells were counted. The number of cells was determined by acridine orange direct count (AODC) (Hobbie and others, 1977). Sterile sodium citrate (0.1 molar,

Table 21. Average chloroform and bromoform contents of vials from aerobic, unenriched sediment microcosm experiments using ground water collected from well 7N/12W-27P2 (well 4-32) on March 6, 1998

[Samples were analyzed by the U.S. Geological Survey in Menlo Park, California. Sterile systems were autoclaved; live systems contain viable bacteria. Averages were derived from two to four replicate analyses. $CHCl_3$, chloroform; $CHBr_3$, bromoform. μg, microgram]

Incubation day	$CHCl_3$			
	Sterile		Live	
	Average (μg)	Standard deviation	Average (μg)	Standard deviation
2	1.24	0.08	1.21	0.04
24	1.22	.09	1.30	.16
52	1.13	.16	1.31	.17
73	1.12	.01	1.17	.15
97	1.22	.04	1.12	.12
145	1.47	.21	1.45	.01
	$CHBr_3$			
	Sterile		Live	
	Average (μg)	Standard deviation	Average (μg)	Standard deviation
2	5.97	0.30	6.11	0.59
25	5.82	.18	5.58	.37
53	5.39	.25	5.80	.56
66	4.87	.25	4.64	.47
95	4.65	.07	4.64	.53
143	5.05	.23	5.39	.21

Table 22. Average chloroform and bromoform contents of vials from aerobic, enriched sediment microcosm experiments using ground water collected from well 7N/12W-27P2 (well 4-32) on March 6, 1998

[Samples were analyzed by the U.S. Geological Survey in Menlo Park, California. Sterile systems were autoclaved; live systems contain viable bacteria. Averages were derived from two to four replicate analyses. $CHCl_3$, chloroform; $CHBr_3$, bromoform. μg, microgram]

Incubation day	$CHCl_3$			
	Sterile		Live	
	Average (μg)	Standard deviation	Average (μg)	Standard deviation
1	7.99	1.26	7.83	0.08
26	9.18	2.77	9.05	.10
52	7.83	.42	9.86	1.22
75	7.89	.12	7.97	.14
99	7.72	.55	8.20	1.00
146	6.93	.28	8.30	.15
	$CHBr_3$			
	Sterile		Live	
	Average (μg)	Standard deviation	Average (μg)	Standard deviation
1	15.50	0.83	20.04	5.45
27	19.04	4.45	26.68	5.01
68	26.69	2.15	29.07	4.19
97	23.43	3.29	25.98	2.44
145	23.44	1.98	24.68	1.26

Table 23. Average chloroform and bromoform contents of vials from anaerobic, enriched sediment microcosm experiments using ground water collected from well 7N/12W-27P2 (well 4-32) on March 6, 1998

[Samples were analyzed by the U.S. Geological Survey in Menlo Park, California. Sterile systems were autoclaved; live systems contain viable bacteria. Averages were derived from two to four replicate analyses. $CHCl_3$, chloroform; $CHBr_3$, bromoform. µg, microgram]

Incubation day	$CHCl_3$ Sterile Average (µg)	Sterile Standard deviation	Live Average (µg)	Live Standard deviation		
1	4.32	0.87	5.16	0.43		
11	4.54	.17	4.22	.88		
53	4.55	.75	3.34	.37		
74	4.73	.59	3.12	.28		
98	3.94	.39	2.56	.05		
145	4.18	.36	3.00	.18		
	$CHBr_3$					
	Sterile Average (µg)	**Sterile Standard deviation**	**Live: Vial 1 Average (µg)**	**Live: Vial 1 Standard deviation**	**Live: Vial 2 Average (µg)**	**Live: Vial 2 Standard deviation**
2	10.50	1.63	12.49	5.52	13.33	7.41
14	10.01	1.71	11.14	5.52	0	0
14.5					[1]65.77	7.41
15	8.18	.14	7.56	2.82	7.75	2.82
43	7.77	1.48	9.81	1.31	0	0
43.5					[1]11.28	1.95
44	6.94	0.59	4.49	.18	10.45	1.25
45	9.13	.70	8.64	2.82	10.68	4.20
53					.13	.03
56	8.63	1.78	9.41	1.16		
56.5					[1]45.38	4.69
70	7.79	.04	7.68	2.82	5.07	.22

[1] Additional $CHBr_3$ was added.

pH = 6.6) was added during filtration to remove background fluorescence (Harvey, 1987).

Results

Sediment Microcosm Experiments

Average $CHCl_3$ and $CHBr_3$ contents of vials from the sediment microcosm experiments are given in tables 21, 22, and 23. $CHCl_3$ and $CHBr_3$ contents of the sterile and live vials for the aerobic, unenriched sediment microcosms remained essentially unchanged during the 145 days of incubation (table 21). $CHCl_3$ and $CHBr_3$ contents of the sterile and live vials in the aerobic, enriched sediment microcosms also remained essentially unchanged during the 145 days of incubation (table 22), as did the $CHCl_3$ contents of the sterile and live vials in the anaerobic, enriched sediment microcosms (table 23). However, different behavior was observed in the anaerobic, enriched sediment microcosms spiked with $CHBr_3$. Because this environmental condition was considered the most likely to promote biodegradation, a second vial of the anaerobic, enriched sediment microcosm containing live bacteria and $CHBr_3$ was incubated. In this vial, $CHBr_3$ was consumed and the vial was respiked with additional $CHBr_3$ after 14.5, 43.5, and 56.5 days of incubation (table 23).

Water Enrichment Experiments

Average $CHCl_3$ and $CHBr_3$ contents of vials used in the water enrichment and filter control experiments are given in tables 24 and 25, respectively. $CHCl_3$ and $CHBr_3$ contents of the vials containing sterile extraction water or extraction water amended with centrifuged bacteria, and $CHCl_3$ contents of the vials containing extraction or ground water amended with filtered bacteria remained essentially unchanged during the 83-day incubation period (table 24). $CHBr_3$ contents of the vials containing extraction or ground water amended with filtered bacteria decreased during the 83-day incubation period (table 24). $CHCl_3$ and $CHBr_3$ contents of the vials containing filtered extraction water with or without a sterile filter added remained essentially unchanged during the 29-day incubation period (table 25).

Bacterial Densities

The average bacterial cell densities in water samples determined by acridine orange direct counting are given in table 26. Average bacterial cell densities in ground water collected from well 4-32 and in extraction water from wells 4-13, 4-33, and 4-42 ranged from 2,900 cells/mL (cells per milliliter) to 50,000 cells/mL

Table 24. Average chloroform and bromoform contents of vials from water enrichment experiments using ground water collected from well 7N/12W-27P2 (well 4-32) on March 6, 1998, or extraction water collected from well 7N/12W-27P2 (well 4-32) on August 14, 1998

[Samples were analyzed by the U.S. Geological Survey in Menlo Park, California. Sterile systems were autoclaved; live systems contain viable bacteria. Averages were derived from two to four replicate analyses. $CHCl_3$, chloroform; $CHBr_3$, bromoform. µg, microgram]

Incubation day	Sterile extraction water				Live extraction water with centrifuged bacteria				Live extraction water with filtered bacteria				Live ground water with filtered bacteria			
	$CHCl_3$		$CHBr_3$		$CHCl_3$		$CHBr_3$		$CHCl_3$		$CHBr_3$		$CHCl_3$		$CHBr_3$	
	Average (µg)	Standard deviation	Average (µg)	Standard deviation	Average (µg)	Standard deviation	Average (µg)	Standard deviation	Average (µg)	Standard deviation	Average (µg)	Standard deviation	Average (µg)	Standard deviation	Average (µg)	Standard deviation
1	5.76	0.50	10.18	2.36	6.03	0.36	13.19	0.87	5.79	0.12	14.50	0.26	5.25	0.12	15.31	1.91
13	5.74	.62	9.69	.20	6.18	.14	11.29	.33	6.08	.22	9.23	.73	4.97	.10	9.50	.40
34	5.57	.29	10.98	.82	5.99	.09	11.59	.40	5.89	.00	6.76	.00	5.70	.00	7.02	.00
83	5.00	.26	12.83	.49	5.52	.38	11.85	1.38	5.06	.58	6.49	1.53	4.46	.34	5.27	.64

Table 25. Average chloroform and bromoform contents of vials from filter control experiments using groound water collected from well 7N/12W-27P2 (well 4-32) on July 22, 1999

[Samples were analyzed by the U.S. Geological Survey in Menlo Park, California. Water was sterilized by filtration. Averages were derived from two to four replicate analyses. $CHCl_3$, chloroform; $CHBr_3$, bromoform. µg, microgram]

Incubation day	Extraction water				Extraction water with filter			
	$CHCl_3$		$CHBr_3$		$CHCl_3$		$CHBr_3$	
	Average (µg)	Standard deviation	Average (µg)	Standard deviation	Average (µg)	Standard deviation	Average (µg)	Standard deviation
1	6.64	0.26	13.35	0.62	6.48	0.36	11.89	0.36
4	6.37	.20	10.92	.33	6.37	.11	10.49	.49
20	6.72	.02	11.31	.72	6.47	.37	11.62	.37
21	6.78	.04	11.67	.63	6.62	.01	11.12	.17
29	7.22	.59	10.72	.67	7.26	.22	11.14	.22

(table 26). Wells 4-13, 4-33, and 4-42 are outside of the area directly influenced by injection into well 4-32 (Metzger and others, 2002). The average bacterial cell density in the chlorinated injection water was 9,100 cells/mL (table 26). Average bacterial cell densities in extraction water from well 4-32 and water from the nested piezometers 27P6–8 ranged from 75,000 cells/mL to 370,000 cells/mL (table 26).

Sorption of Trihalomethanes to Aquifer Sediments

The potential for sorption of THMs by the sediments in the aquifer was investigated experimentally by spiking mixtures of sediment and THM-free laboratory water with THMs and measuring the resulting THM concentrations in the water.

Experimental Method

The sediment sample used for the sorption experiment came from the core taken from the depth corresponding to that of the screened interval for piezometer 27P6 (table 2). This sample was chosen because it was relatively fine grained in comparison with other sediment layers in the cores. Finer grained sediments generally have a greater capacity for sorption (for example, Walton and others, 1992). Sediment water content was 15.54 percent by mass and was determined by freeze-drying three aliquots of sediment (standard deviation was 0.17 percent for the three determinations). Mixtures of sediment and water were prepared in 59-mL amber glass serum vials. The sediment content of the mixtures was 20 percent (by

Table 26. Average bacterial cell densities in water collected from wells during the third injection, storage, and recovery cycle (March 1998 through April 1999), Lancaster, Antelope Valley, California

[Samples analyzed by the U.S. Geological Survey in Menlo Park, California. Bacterial density determined by acridine orange direct counting. Averages derived from three replicate aliquots counted for each sample. cells/mL, bacterial cells per milliliter]

Date	Sample type	Average bacterial density (cells/mL)	Standard deviation
	Well 7N/12W-27P2 (well 4-32)		
03/04/1998	Ground water	50,000	45,000
06/16/1998	Injection	9,100	35,000
08/17/1998	Extraction	160,000	100,000
09/03/1998	Extraction	75,000	51,000
10/07/1998	Extraction	80,000	56,000
	Well 7N/12W-27J4 (well 4-13)		
10/07/1998	Extraction	14,000	23,000
	Well 7N/12W-27H3 (well 4-33)		
10/07/1998	Extraction	2,900	17,000
	Well 7N/12W-27J6 (well 4-42)		
10/07/1998	Extraction	15,000	31,000
	Piezometer 7N/12W-27P8		
08/04/1998		220,000	98,000
09/03/1998		100,000	66,000
10/07/1998		350,000	99,000
11/04/1998		97,000	46,000
	Piezometer 7N/12W-27P7		
08/04/1998		210,000	120,000
09/03/1998		260,000	100,000
10/07/1998		370,000	94,000
11/04/1998		140,000	57,000
	Piezometer 7N/12W-27P6		
08/04/1998		280,000	90,000
09/03/1998		150,000	89,000
10/07/1998		180,000	57,000
11/04/1998		93,000	56,000

Table 27. Trihalomethane concentration data from sediment-water equilibration experiments

[Sediment sample from core corresponding to perforated interval for piezometer 7N/12W-27P6 (fig. 2, table 2), Lancaster, Antelope Valley, California. Samples analyzed by the U.S. Geological Survey in Sacramento, California. THM, trihalomethane; $CHCl_3$, chloroform; $CHCl_2Br$, bromodichloromethane; $CHClBr_2$, dibromochloromethane; $CHBr_3$, bromoform. µg/L, microgram per liter]

Equilibration time (week)	Sediment content (weight percent)	THM spike concentration (µg/L)	THMs				Total THMs (µg/L)
			$CHCl_3$ (µg/L)	$CHCl_2Br$ (µg/L)	$CHClBr_2$ (µg/L)	$CHBr_3$ (µg/L)	
1	0	0	0.08	0.00	0.00	0.00	0.1
1	0	155	36.4	36.3	36.8	36.1	145.6
1	0	155	38.5	37.9	39.9	40.2	156.5
1	0	155	38.3	39.2	43.8	42.9	164.1
1	4	0	.03	.01	.02	.04	.1
1	4	155	34.6	36.0	39.1	38.0	147.7
1	4	155	40.9	40.0	43.8	42.1	166.8
1	4	155	31.9	33.5	36.0	37.7	139.1
1	20	155	36.9	38.3	39.0	35.9	150.1
3	0	0	.27	.22	.25	.04	.8
3	0	175	43.7	38.3	40.5	51.5	174.0
3	0	175	40.7	37.8	41.5	54.1	174.1
3	0	175	46.8	39.2	39.4	52.0	177.3
3	4	0	.14	.11	.19	.19	.6
3	4	175	34.3	33.4	39.3	51.4	158.4
3	4	175	35.1	33.3	39.0	54.5	161.8
3	4	175	30.4	30.2	34.8	46.9	142.3
3	4	175	35.0	31.3	35.1	45.0	146.5
3	20	175	38.1	33.4	34.3	44.6	150.3
3	20	175	44.5	40.1	41.2	52.6	178.4
3	20	175	44.6	40.4	42.1	55.9	183.1

mass) or 4 percent dry sediment. The percentages were based on sediment dry weight and then corrected for sediment water content to prepare the mixtures; thus the aliquots of sediment used in the experiments were not subjected to drying.

The water used in the experiments was organic-carbon-free, THM-free water and was prepared by filtering the laboratory de-ionized water through a second filtration system consisting of an ultraviolet irradiation unit and an activated carbon filtration unit (PichTech, Hydro Service and Supplies, Inc.). This water was analyzed regularly for DOC and THM concentrations and, in all cases, measured concentrations were well below detection limits (measured total THM less than 0.01 µg/L and measured DOC less than 0.05 mg/L).

The THM spike was prepared from a Supelco THM standard solution containing about 100 micrograms per milliliter of each of the four THM species dissolved in methanol. The Supelco solution was diluted in methanol to produce a working spike solution. The vials for the 1-week experiments were spiked with 155 µg/L of total THMs and the vials for the 3-week experiments were spiked with 175 µg/L of total THMs (table 27).

Twelve experimental conditions were investigated by varying the sediment content of the slurries, the equilibration time, and the amount of THM spike added. Replicate vials were prepared for the combinations of conditions that included THM spike and sediment. After the sediment, water, and THM spike were added to the vials, they were sealed with no headspace with aluminum crimp top seals and Teflon-faced septa. The sediment was kept in suspension during equilibration by placing the vials in a rotating drum. After completion of the equilibration time, all the samples were filtered by being drawn into a large gas-tight syringe, then pressure-filtered through a 0.1-µm cartridge filter fitted on the luer tip of the syringe. THM concentrations were analyzed at the USGS Sacramento laboratory using the method described previously in the "Water-Quality Monitoring at Wells, Analytical Methods" section.

Results

THM concentrations in the water from the slurries equilibrated for 1 and 3 weeks are shown in figure 8 and given in table 27. For the samples equilibrated for 1 week, the total THM concentrations in the control samples containing only water were 145.6 to 164.1 µg/L and in the slurries containing sediment, 139.1 to 166.8 µg/L. For the samples equilibrated for 3 weeks, the total THM concentrations in the control samples containing only water were 174.0 to 177.3 µg/L and in the slurries containing sediment, 142.3 to 183.1 µg/L (table 27).

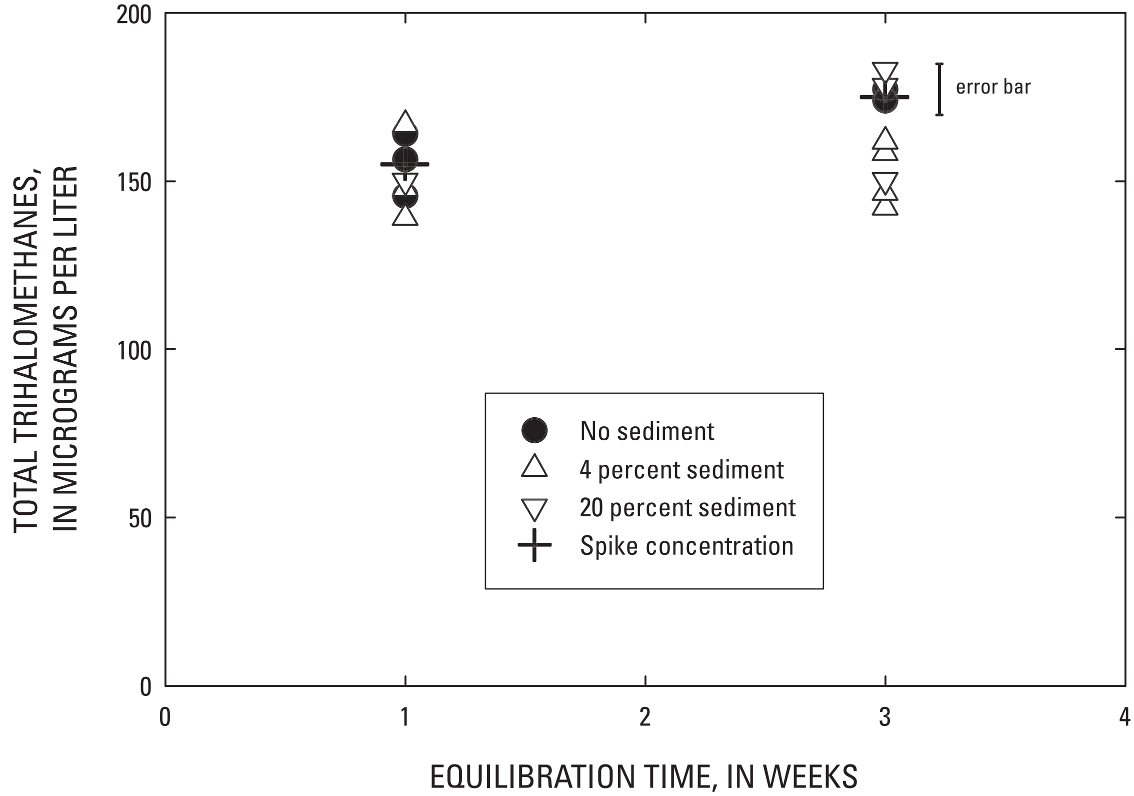

Figure 8. Total trihalomethane concentration in water from sediment-water slurries that were equilibrated for 1 and 3 weeks; the sediment sample is from the core taken from the depth corresponding to that of the screened interval for piezometer 7N/12W-27P6 (fig. 2, table 2), Lancaster, Antelope Valley, California. Analytical precision is indicated by the error bar.

Summary

This report is one of a series of U.S. Geological Survey (USGS) reports describing a series of tests of injection, storage, and recovery in Lancaster, Antelope Valley, California. The tests were designed to assess the feasibility of artificially recharging ground water as part of a management strategy to address increasing water demands and avoid future land subsidence. During the third cycle (March 1998 through April 1999), research included investigation of the formation and fate of trihalomethanes (THM) in the aquifer. The investigation had five components: monitoring water quality during the injection and extraction phases of the cycle, examining the formation of THMs from the injection water, using a conservative tracer in the injection water to evaluate mixing, assessing the potential for biodegradation of THMs by aquifer bacteria, and assessing the potential for sorption of THMs to aquifer sediments. This report includes a description of the design of the five components of the THM study, explanations of the experimental and analytical methods, and a presentation of the resulting data.

Fifty-eight million gallons of chlorinated water imported from the State Water Project was injected into the aquifer through well 7N/12W-27P2 (well 4-32) in a Los Angeles County Department of Public Works well field in Lancaster between April 15 and June 16, 1998. One hundred fifty million gallons of water was extracted from well 4-32 between June 30, 1998, and April 29, 1999. Samples were collected from well 4-32 during the injection and extraction periods of the cycle to monitor water quality. A sample of ground water was collected from the well before injection began. In addition, water samples were collected from a nearby set of nested piezometers, 7N/12W-27P6, 27P7, and 27P8, before the injection period, and during the injection and extraction periods of the cycle.

The USGS analyzed dissolved organic carbon (DOC), residual chlorine, and THM concentrations, and ultraviolet absorbance spectra in 31 samples of injection water from well 4-32. The USGS also analyzed DOC and THM concentrations, and ultraviolet absorbance spectra in 21 samples of extraction water and 1 sample of ground water from well 4-32, and in 21 samples from the nested piezometers. Assessment of quality-assurance and quality-control samples yielded estimates of analytical precision at the 95-percent confidence level for the DOC, residual chlorine, and THM concentrations, and ultraviolet absorbance analyses. The cooperators, the Los Angeles County Department of Public Works and the Antelope Valley–East Kern Water Agency, analyzed THM, residual chlorine, and chloride concentrations, pH, specific conductance, and turbidity in 17 samples of injection water, 58 samples of extraction water, and 1 sample of ground water from well 4-32. Some samples were also analyzed for bromide, nitrate, sulfate, and dissolved solids concentrations.

A storage experiment and a THM-formation potential experiment were done to investigate the formation of THMs in the injection water. In the storage experiment, a total of 57 vials from 30 samples of injection water were stored 1, 2, 4, 8, and 16 weeks prior to analysis of THM concentrations. The purpose of the storage experiment was to assess the capacity of the DOC in the injection water to react with the residual chlorine present at the time of injection. In the trihalomethane formation potential experiment, 29 samples of injection water and 1 sample of ground water were chlorinated under controlled conditions for 7 days prior to analyses of trihalomethane concentrations. The purpose of the trihalomethane formation potential experiment was to assess the maximum capacity of the DOC in the injection water to form THMs in the presence of excess chlorine.

A tracer study was done to evaluate the extent of mixing between injected water and ground water. A conservative, nontoxic tracer, sulfur hexafluoride (SF_6), was added to the injection water throughout the injection period by metered addition of nitrogen gas containing a known concentration of SF_6. The University of California, Santa Barbara, laboratory analyzed SF_6 concentrations in 31 samples of injection water and 23 samples of extraction water from well 4-32, and in 21 samples of water from the nested piezometers.

Sediment microcosm experiments and water enrichment experiments were done to investigate the potential for biodegradation of THMs by aquifer bacteria. In the sediment microcosm experiments, vials containing mixtures of aquifer sediment and ground water were spiked with chloroform ($CHCl_3$) or bromoform ($CHBr_3$), and then incubated for up to 145 days while $CHCl_3$ or $CHBr_3$ contents were monitored. Some sediment microcosms were enriched by adding nutrients and vitamins. Sediment microcosms were incubated under aerobic and anaerobic conditions. For the water enrichment experiments, bacteria were concentrated and extracted from large volumes of ground water and extraction water by centrifugation or filtration. Samples of ground water or extraction water were amended with these concentrated bacteria. The vials containing the water enrichments were spiked with $CHCl_3$ and $CHBr_3$, and incubated for 83 days; THM concentrations were monitored during the incubation period. For both types of experiments, sterilized control vials were also monitored. In addition, average bacterial densities were measured in 1 sample of injection water, 3 samples of extraction water, and 1 sample of ground water from well 4-32; in 12 samples from the nested piezometers; and in 3 samples from nearby wells.

One type of experiment was done to investigate the potential for sorption of THMs to aquifer sediments. Slurries containing clean, laboratory water and 0, 4, and 20 percent aquifer sediment were prepared and spiked with chloroform, bromodichloromethane, dibromochloromethane, and bromoform. The slurries were equilibrated for 1 and 3 weeks, and then filtered and the THM concentrations in the water were measured.

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